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Slepchenkov et al.

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(45) **Date of Patent: Oct. 24, 2023**

(54) **SYSTEMS, DEVICES, AND METHODS FOR RAIL-BASED AND OTHER ELECTRIC VEHICLES WITH MODULAR CASCADED ENERGY SYSTEMS**

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B60L 53/22 (2019.01)
H01M 10/0525 (2010.01)

(52) **U.S. Cl.**
CPC ***B60L 53/22*** (2019.02); *B60L 2200/26* (2013.01); *B60L 2210/10* (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC .. B60L 53/22; B60L 2200/26; B60L 2210/10; B60L 2210/30; B60L 2210/40;
(Continued)

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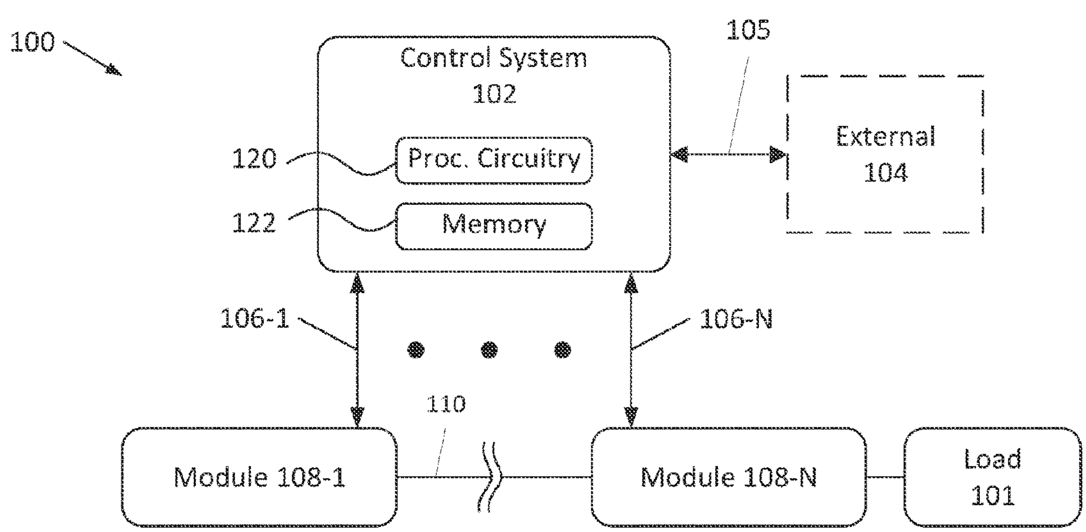
Primary Examiner — Paul Dinh
(74) *Attorney, Agent, or Firm* — Fish & Richardson P.C.

(57) **ABSTRACT**

Example embodiments of systems, devices, and methods are provided for electric vehicles that are subject to intermittent charging, such as rail-based electric vehicles, having one or more modular cascaded energy systems. The one or more modular systems can be configured to supply multiphase, single phase, and/or DC power to numerous motor and auxiliary loads of the EV. If multiple systems or subsystems are present in the EV, they can be interconnected to exchange energy between them in numerous different ways, such as through lines designated for carrying power from the intermittently connected charge source or through the presence of modules interconnected between arrays of the subsystems. The subsystems can be configured as subsystems that supply power for motor loads alone, motor loads in combination with auxiliary loads, and auxiliary loads alone.

22 Claims, 33 Drawing Sheets



Related U.S. Application Data

(60) Provisional application No. 63/084,293, filed on Sep. 28, 2020, provisional application No. 63/029,368, filed on May 22, 2020, provisional application No. 63/025,099, filed on May 14, 2020.

(52) **U.S. Cl.**
CPC *B60L 2210/30* (2013.01); *B60L 2210/40* (2013.01); *H01M 10/0525* (2013.01)

(58) **Field of Classification Search**
CPC .. B60L 1/00; B60L 1/003; B60L 50/70; B60L 50/40; B60L 50/60; B60L 58/20; B60L 53/32; H01M 10/0525; Y02E 60/10; Y02T 10/72; Y02T 90/40; Y02T 10/70; Y02T 10/7072; Y02T 90/12; Y02T 90/14
USPC 320/109
See application file for complete search history.

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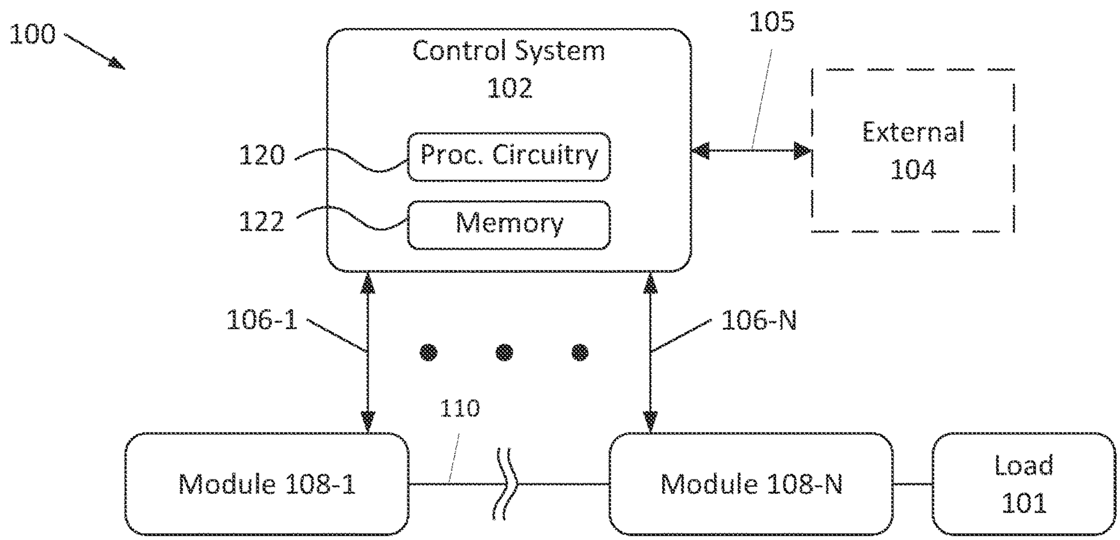
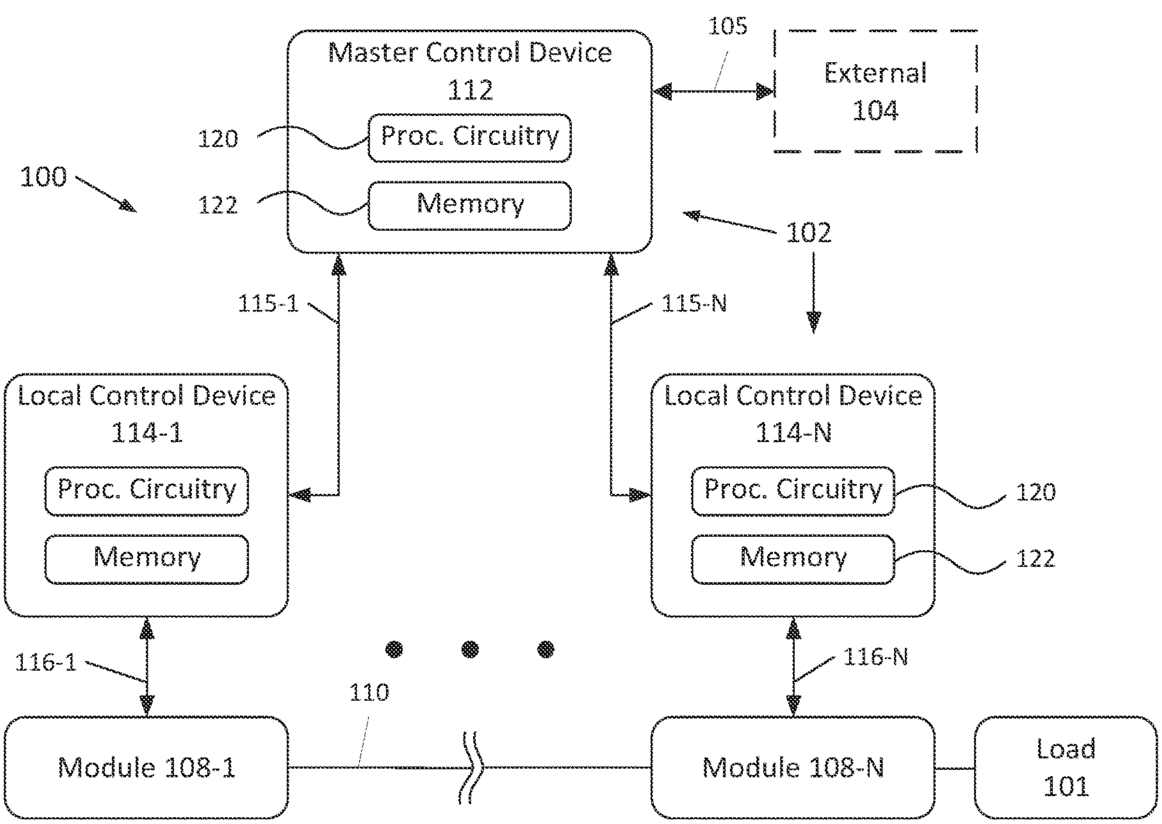


100
Control System
102
105
External
104
120
Proc. Circuitry
122
Memory
106-1
106-N
110
Module 108-1
Module 108-N
Load
101

FIG. 1A



Master Control Device
112
105
External
104
120
Proc. Circuitry
100
122
Memory
102
115-1
115-N
Local Control Device
114-1
Proc. Circuitry
Memory
Local Control Device
114-N
Proc. Circuitry
120
Memory
122
116-1
116-N
110
Module 108-1
Module 108-N
Load
101

FIG. 1B

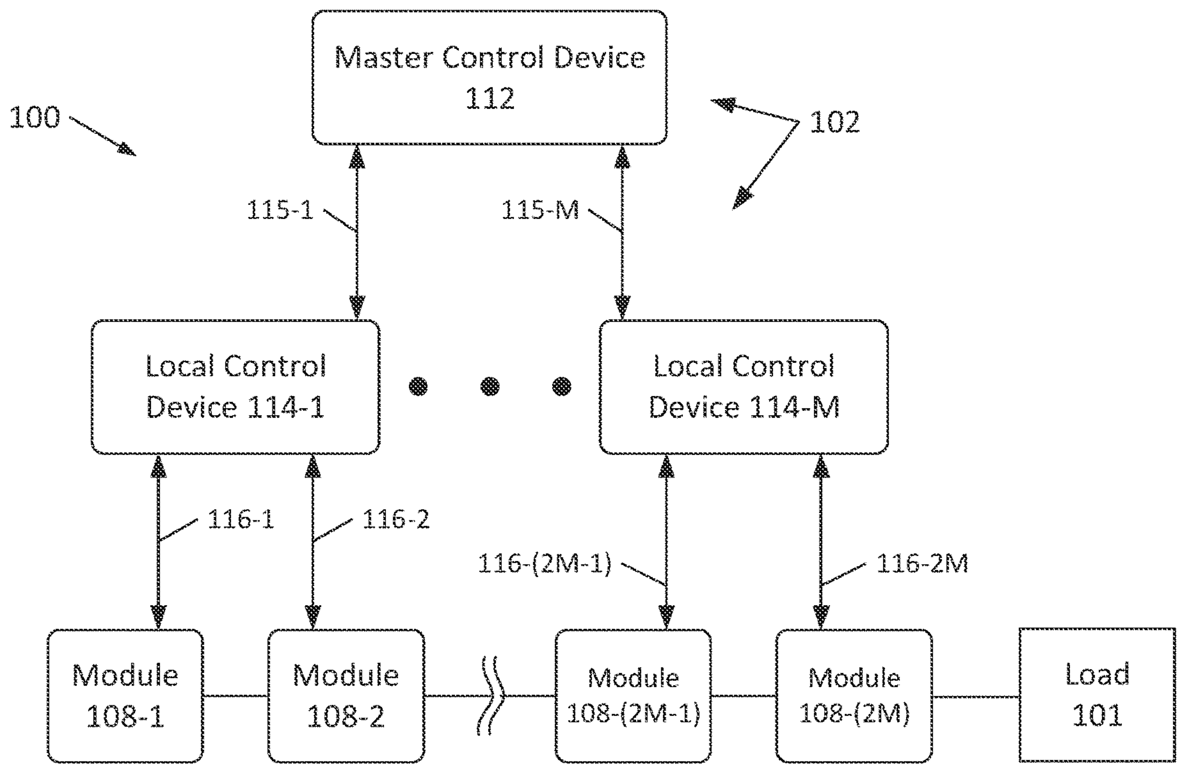


FIG. 1C

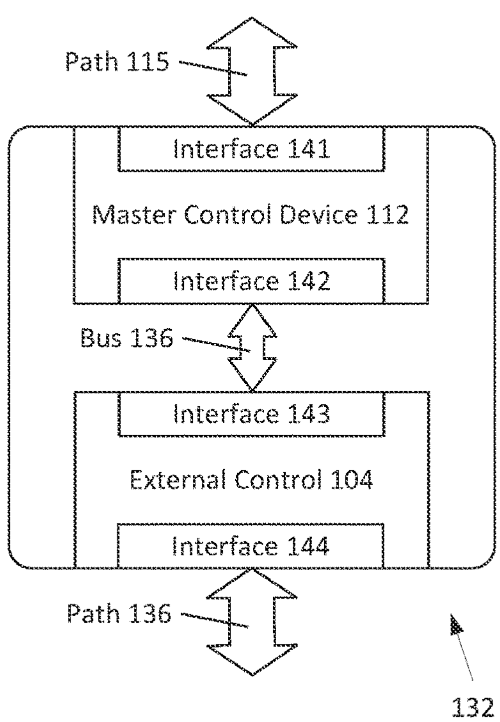


FIG. 1D

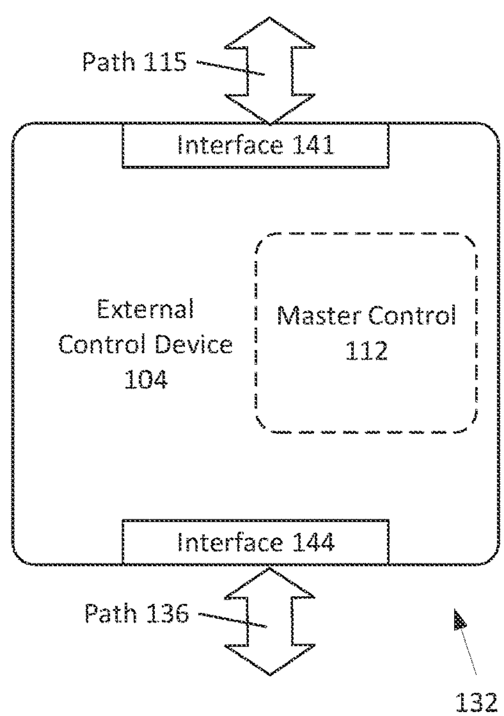


FIG. 1E

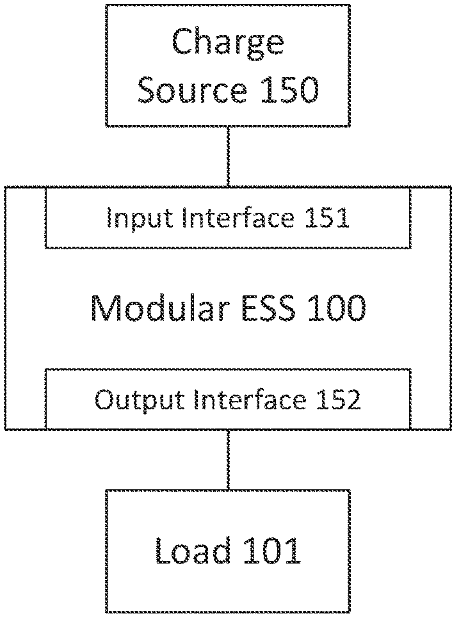


FIG. 1F

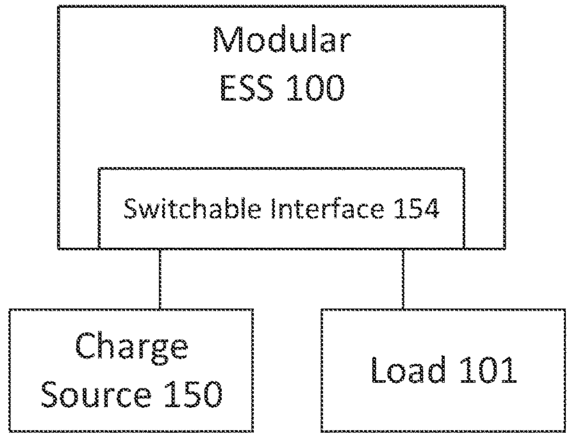


FIG. 1G

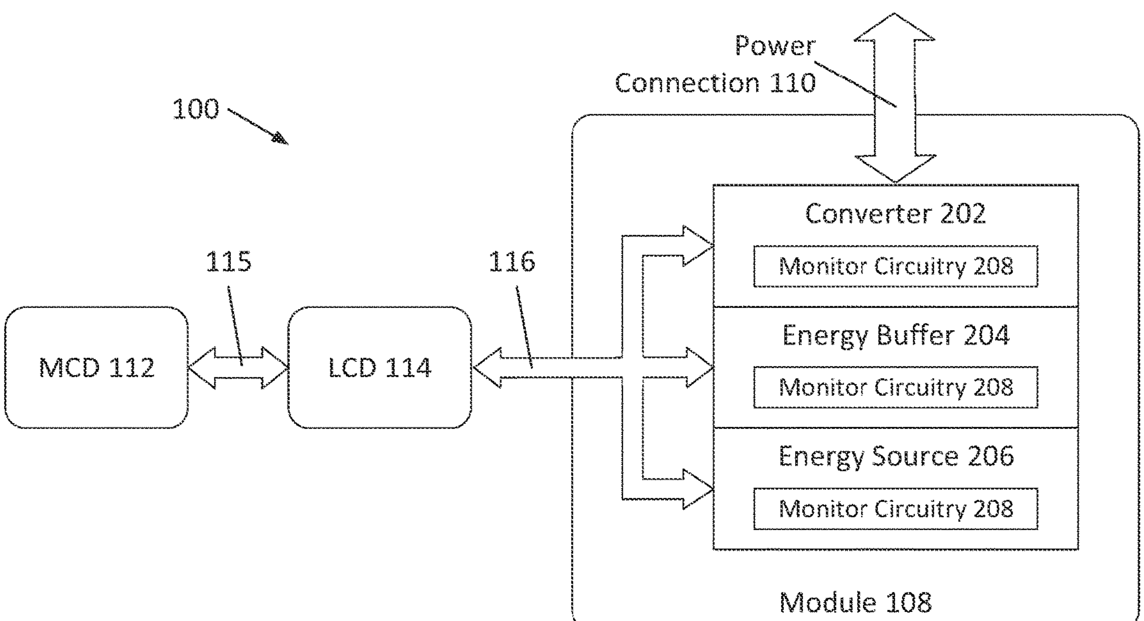


FIG. 2A

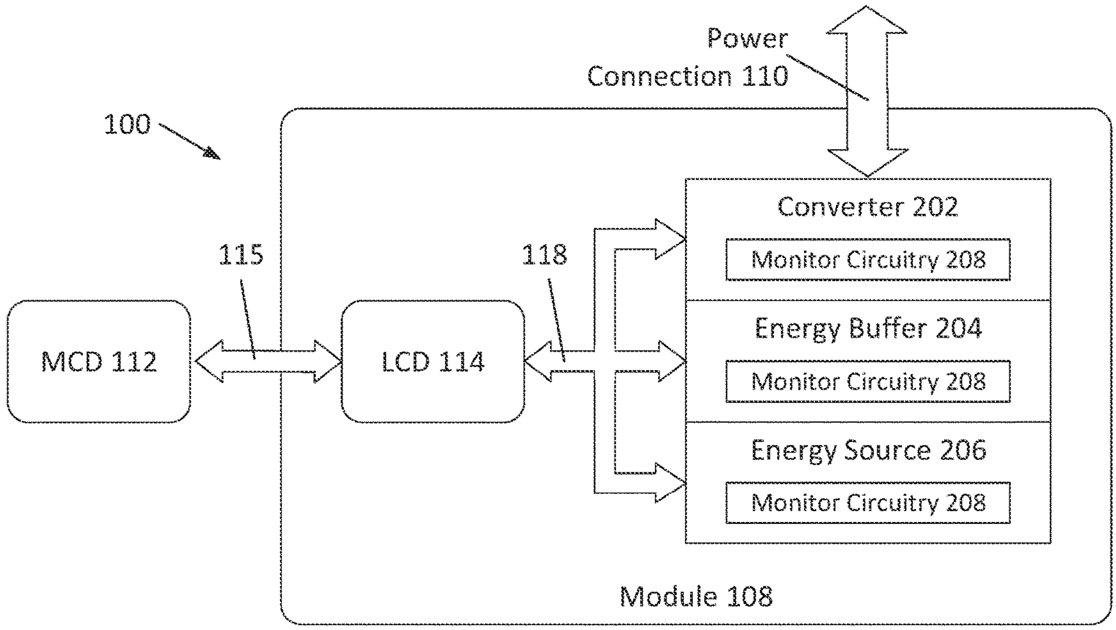


FIG. 2B

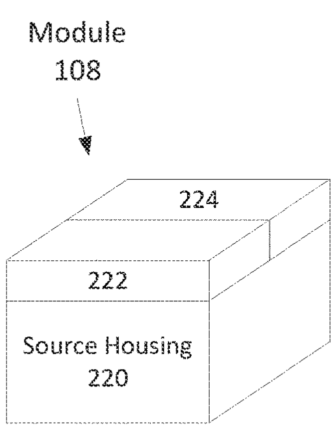


FIG. 2C

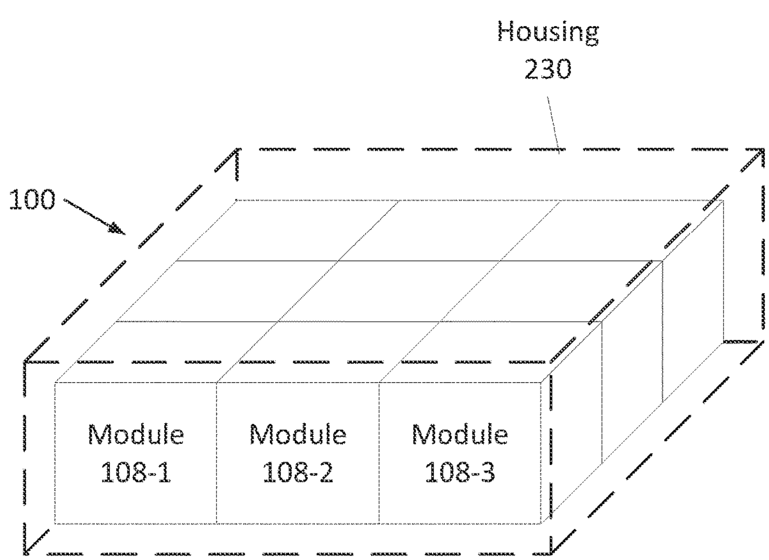
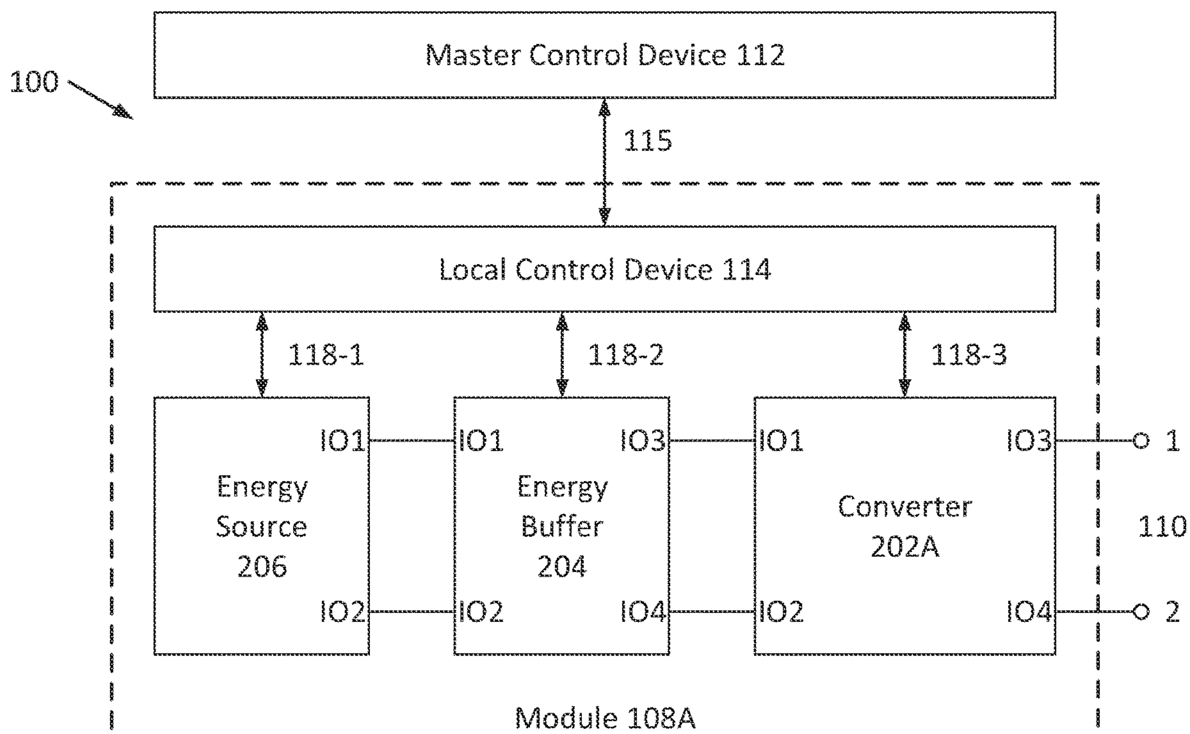


FIG. 2D



Master Control Device 112
100
115
Local Control Device 114
118-1
118-2
118-3
IO1
IO2
Energy Source 206
IO1
IO3
IO2
IO4
Energy Buffer 204
IO1
IO3
IO2
IO4
Converter 202A
1
110
2
Module 108A

FIG. 3A

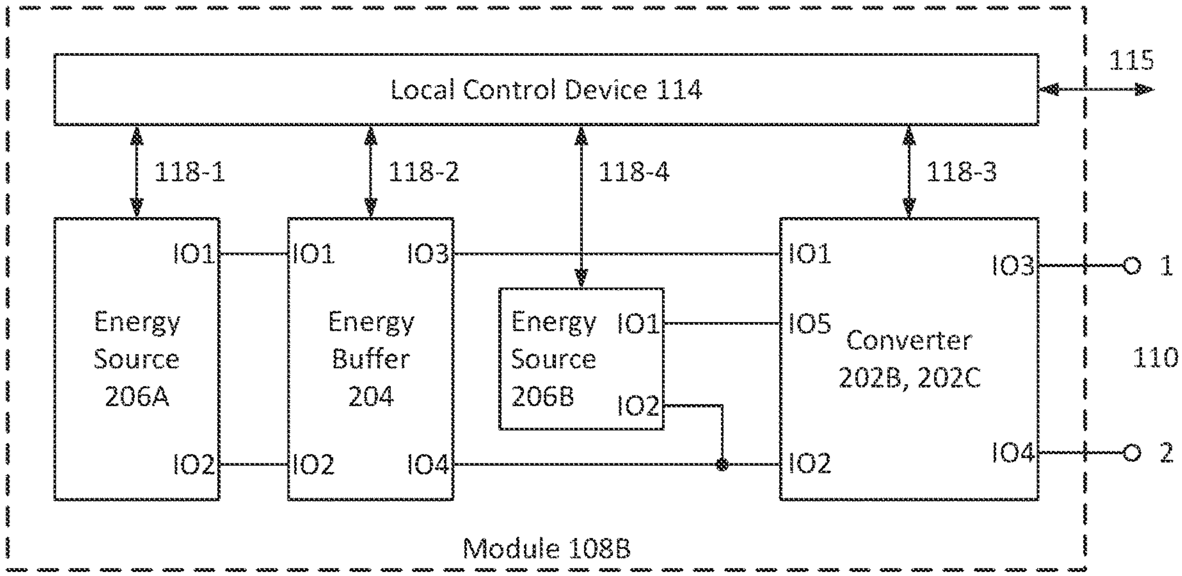

Local Control Device 114
115
118-1
118-2
118-4
118-3
IO1
IO2
Energy Source 206A
IO1
IO3
IO2
IO4
Energy Buffer 204
Energy Source 206B
IO1
IO2
IO1
IO5
IO2
Converter 202B, 202C
IO3
IO4
1
2
110
Module 108B

FIG. 3B

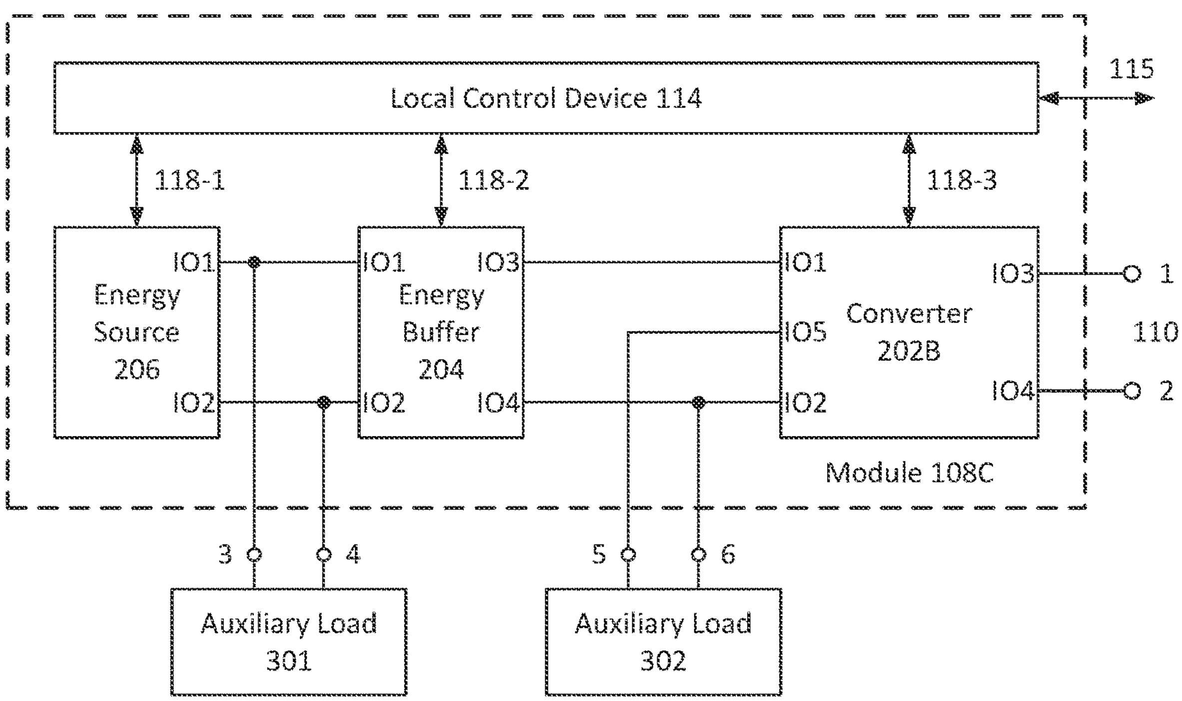

Local Control Device 114
115
118-1
118-2
118-3
IO1
IO2
Energy Source 206
IO1
IO3
IO2
IO4
Energy Buffer 204
IO1
IO5
IO2
Converter 202B
IO3
IO4
1
2
110
Module 108C
3
4
5
6
Auxiliary Load 301
Auxiliary Load 302

FIG. 3C

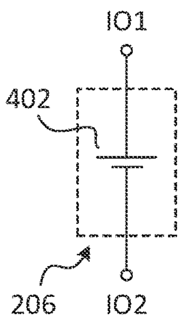


FIG. 4A

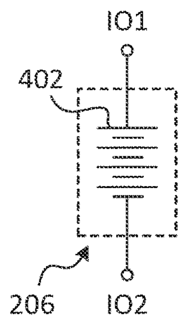


FIG. 4B

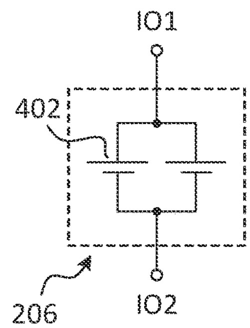


FIG. 4C

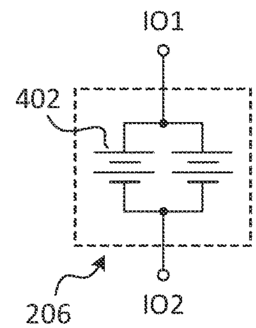


FIG. 4D

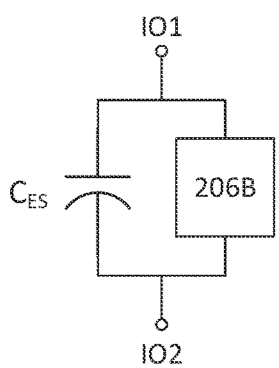


FIG. 4E

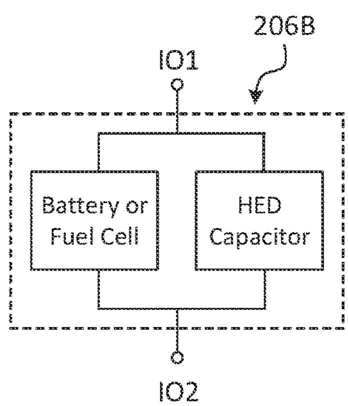


FIG. 4F

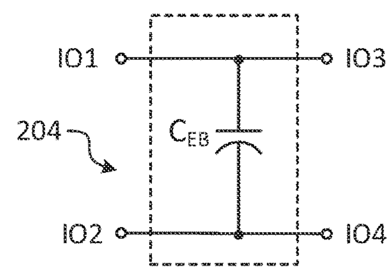


FIG. 5A

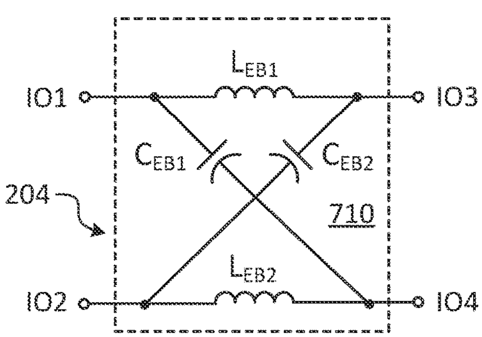


FIG. 5B

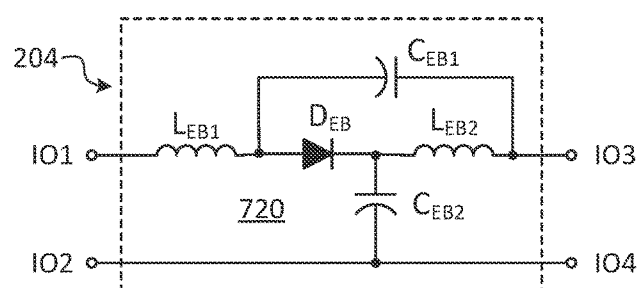
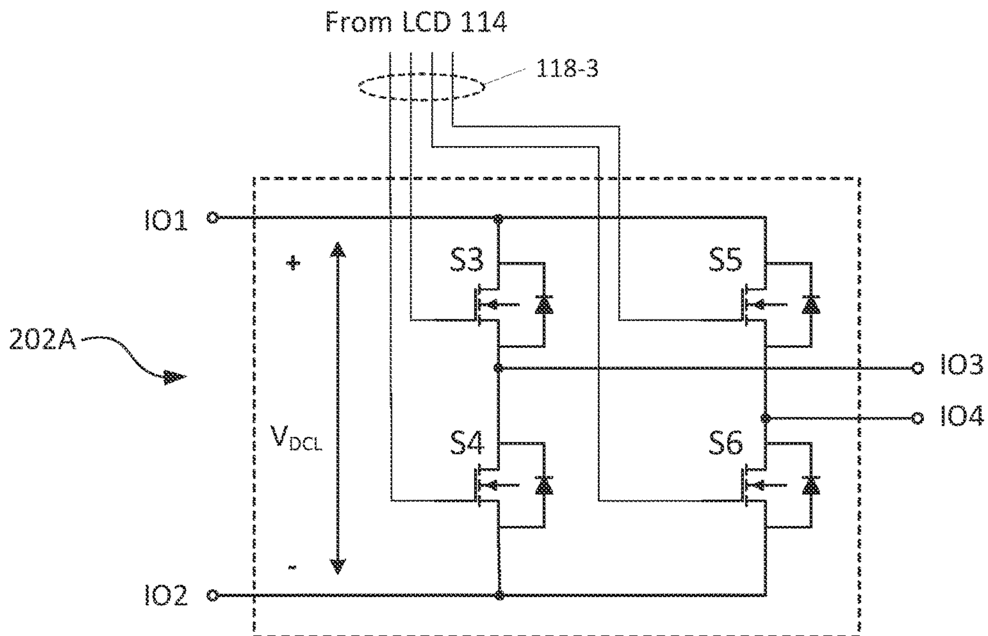
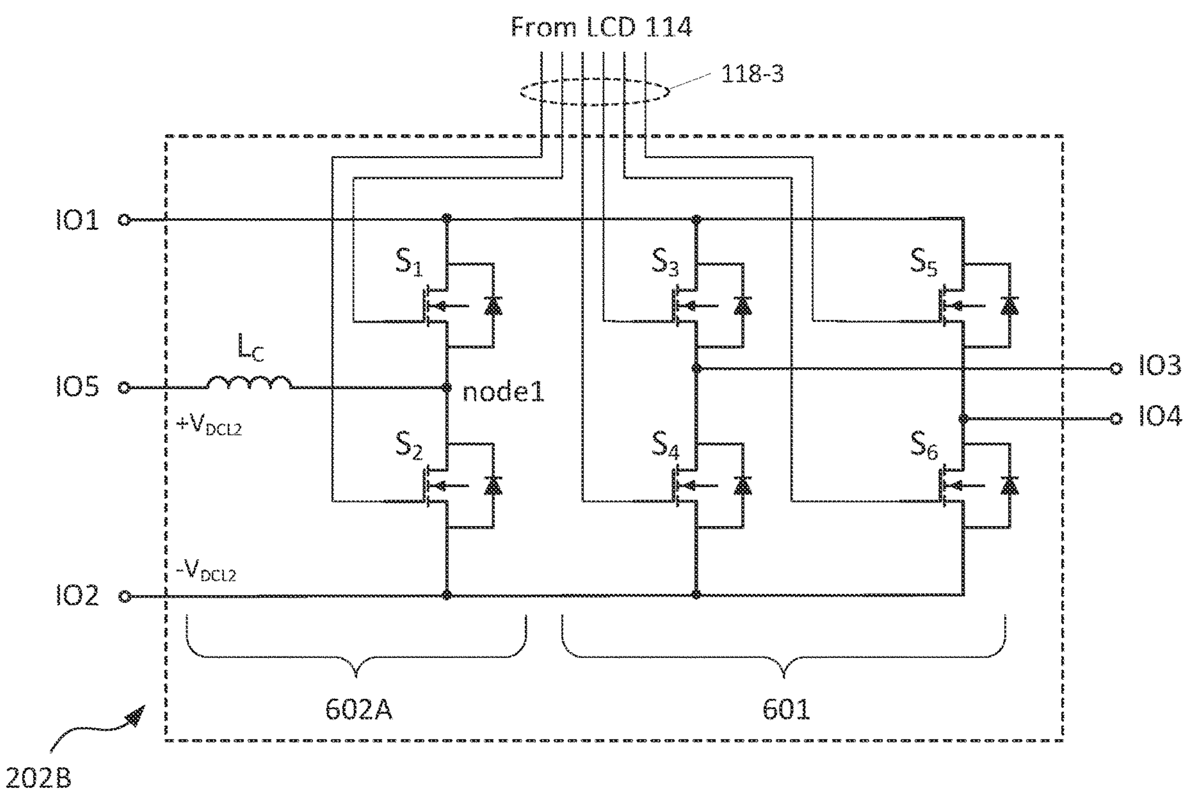


FIG. 5C



From LCD 114
118-3
IO1
S3
S5
+
202A
IO3
IO4
VDCL
S4
S6
-
IO2

FIG. 6A



From LCD 114
118-3
IO1
S1
S3
S5
LC
IO5
node1
IO3
+VDCL2
IO4
S2
S4
S6
-VDCL2
IO2
602A
601
202B

FIG. 6B

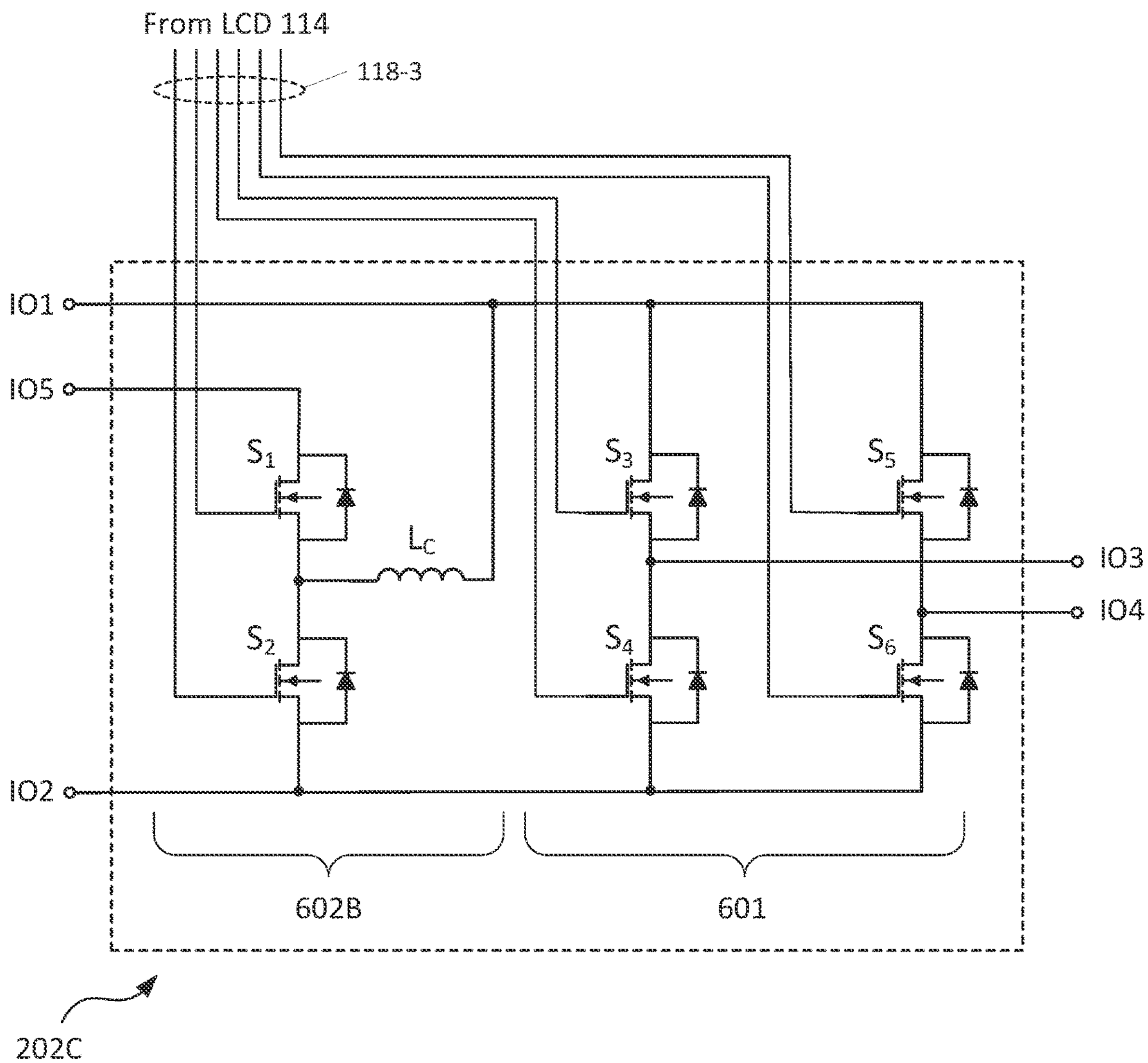

From LCD 114
118-3
IO1
IO5
S1
S3
S5
LC
IO3
IO4
S2
S4
S6
IO2
602B
601
202C

FIG. 6C

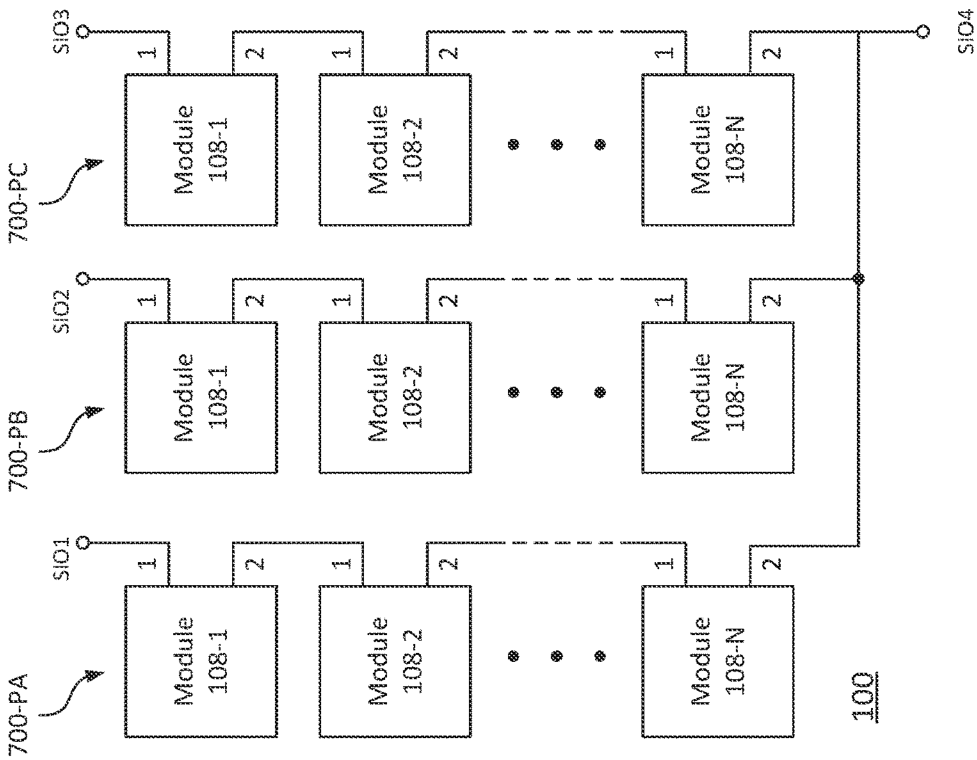


FIG. 7C

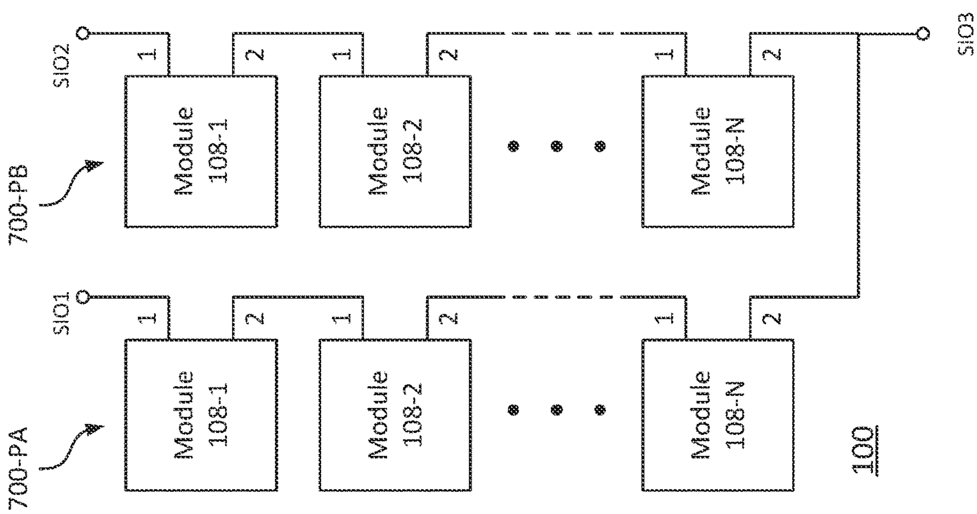


FIG. 7B

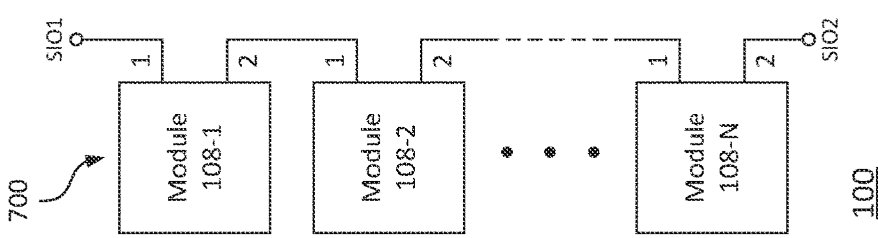


FIG. 7A

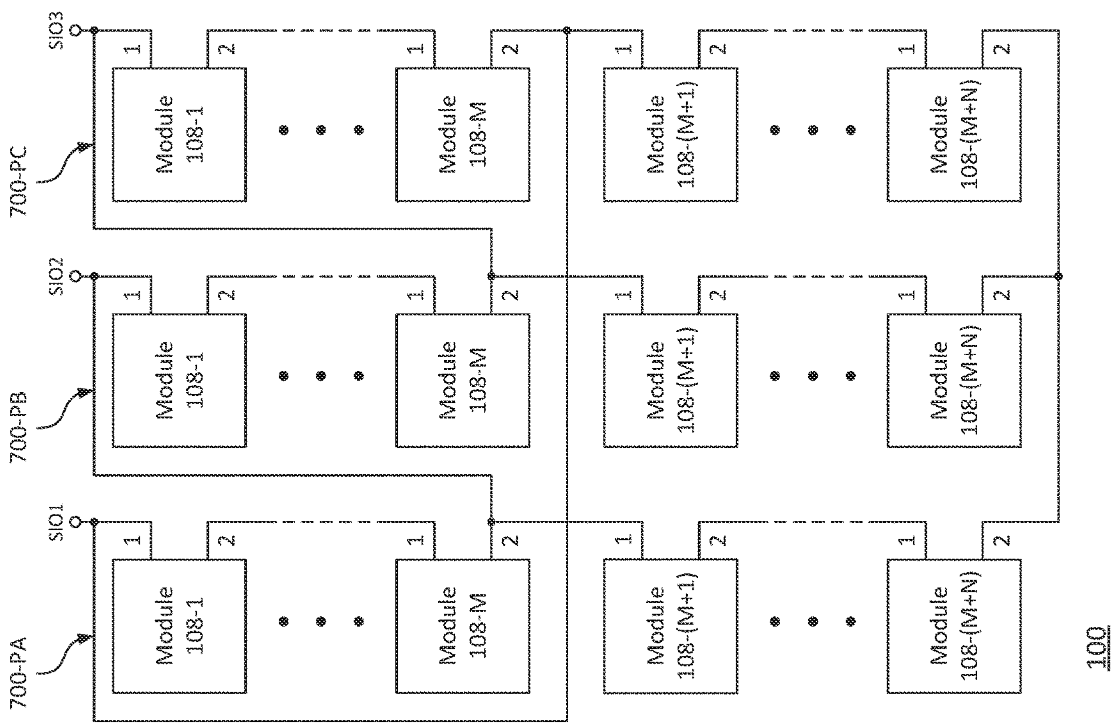

700-PA
700-PB
700-PC
SIO1
SIO2
SIO3
Module 108-1
Module 108-M
Module 108-(M+1)
Module 108-(M+N)
1
2
100

FIG. 7E

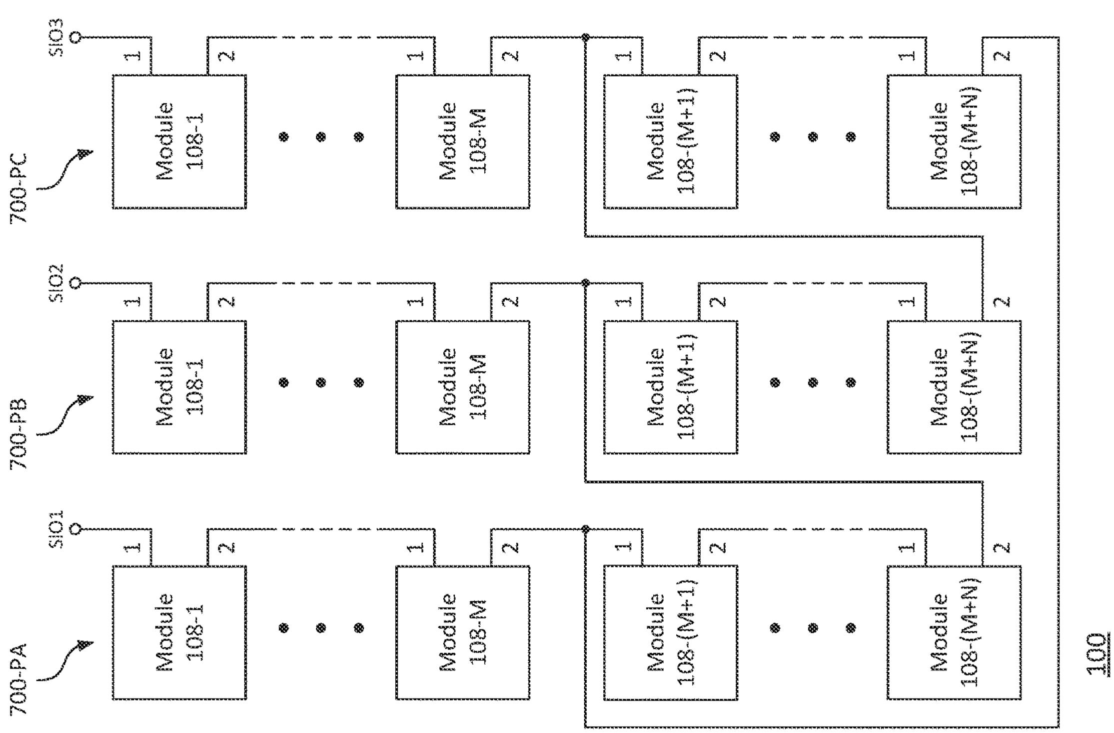

700-PA
700-PB
700-PC
SIO1
SIO2
SIO3
Module 108-1
Module 108-M
Module 108-(M+1)
Module 108-(M+N)
1
2
100

FIG. 7D

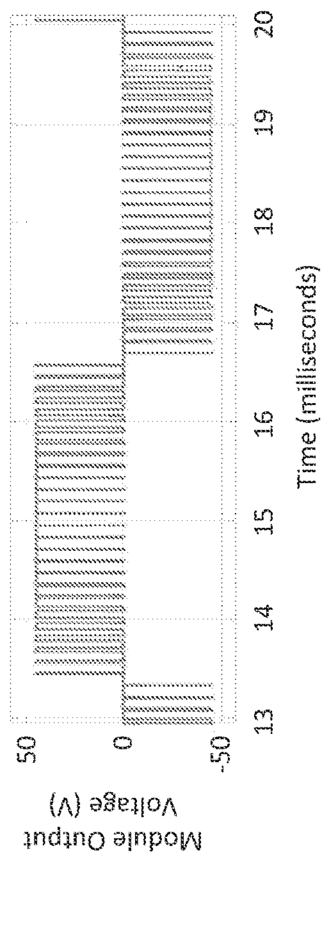


FIG. 8A

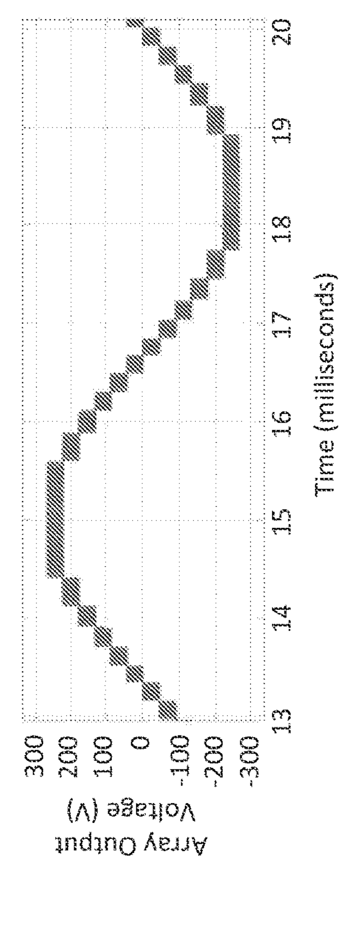


FIG. 8B

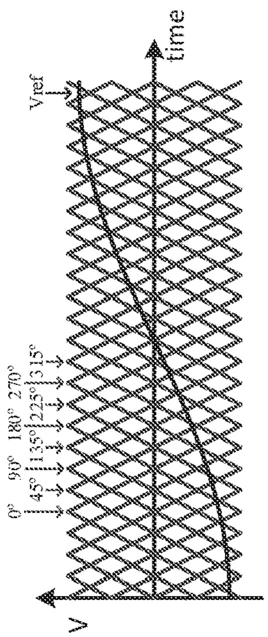


FIG. 8C

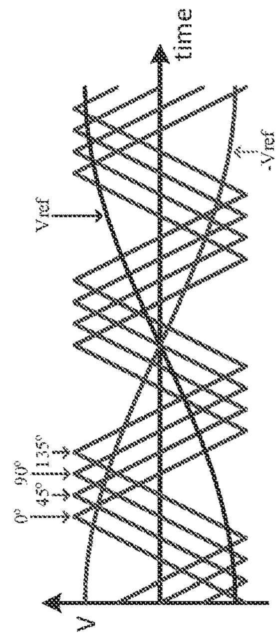


FIG. 8D

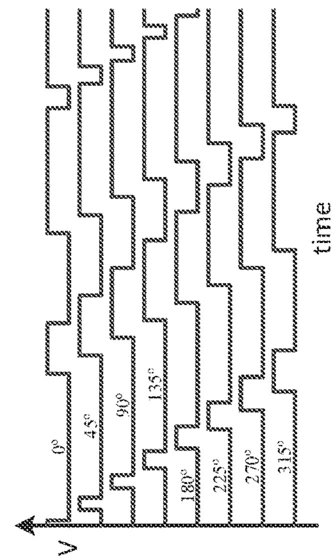


FIG. 8E

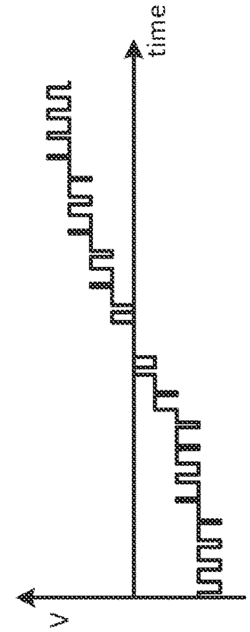


FIG. 8F

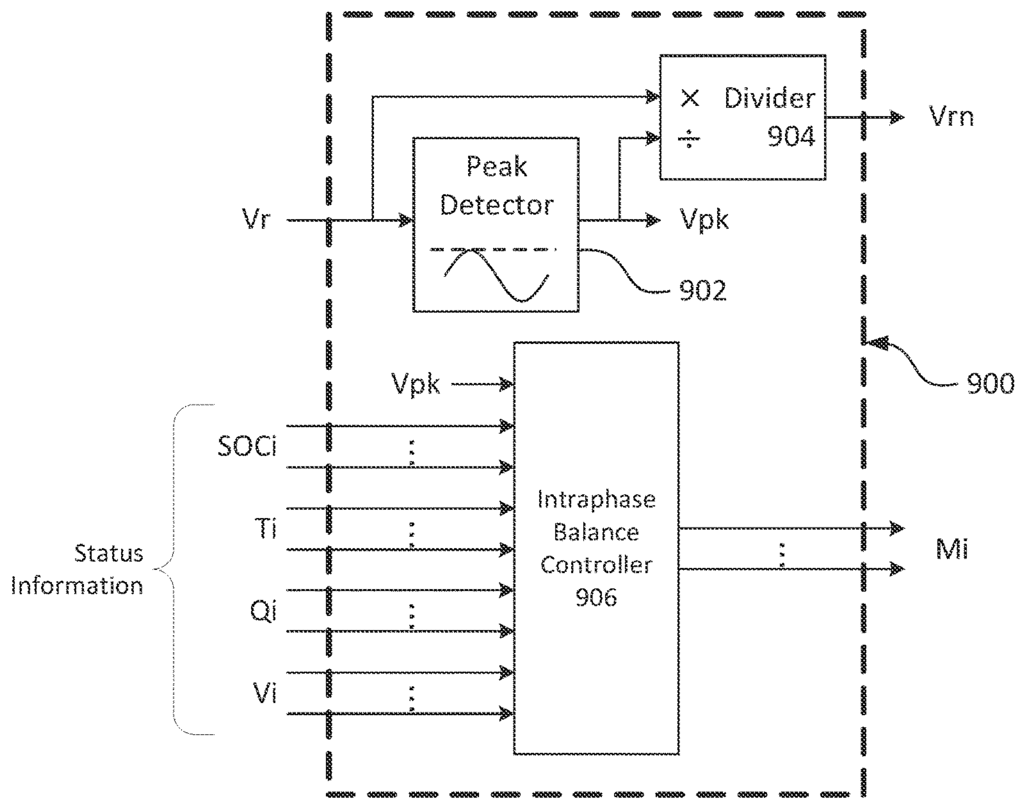

× Divider
÷ 904
Vrn
Peak
Detector
Vr
Vpk
902
900
Vpk
SOCi
Ti
Qi
Vi
Status
Information
Intraphase
Balance
Controller
906
Mi

FIG. 9A

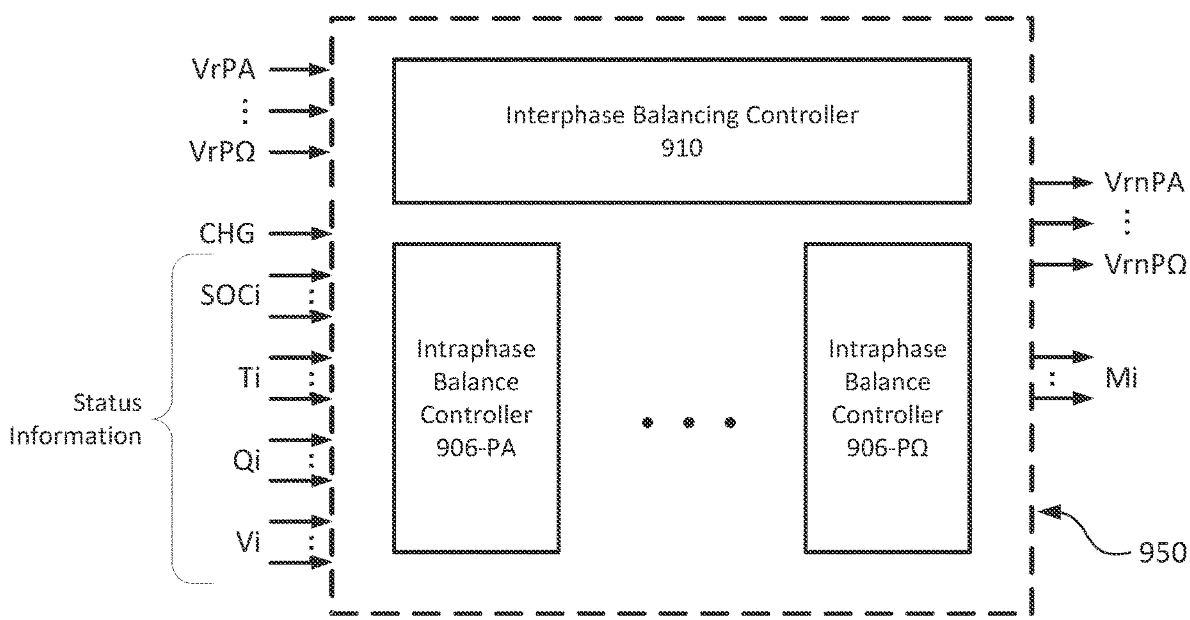

VrPA
VrPΩ
CHG
Interphase Balancing Controller
910
VrnPA
VrnPΩ
SOCi
Ti
Qi
Vi
Status
Information
Intraphase
Balance
Controller
906-PA
Intraphase
Balance
Controller
906-PΩ
Mi
950

FIG. 9B

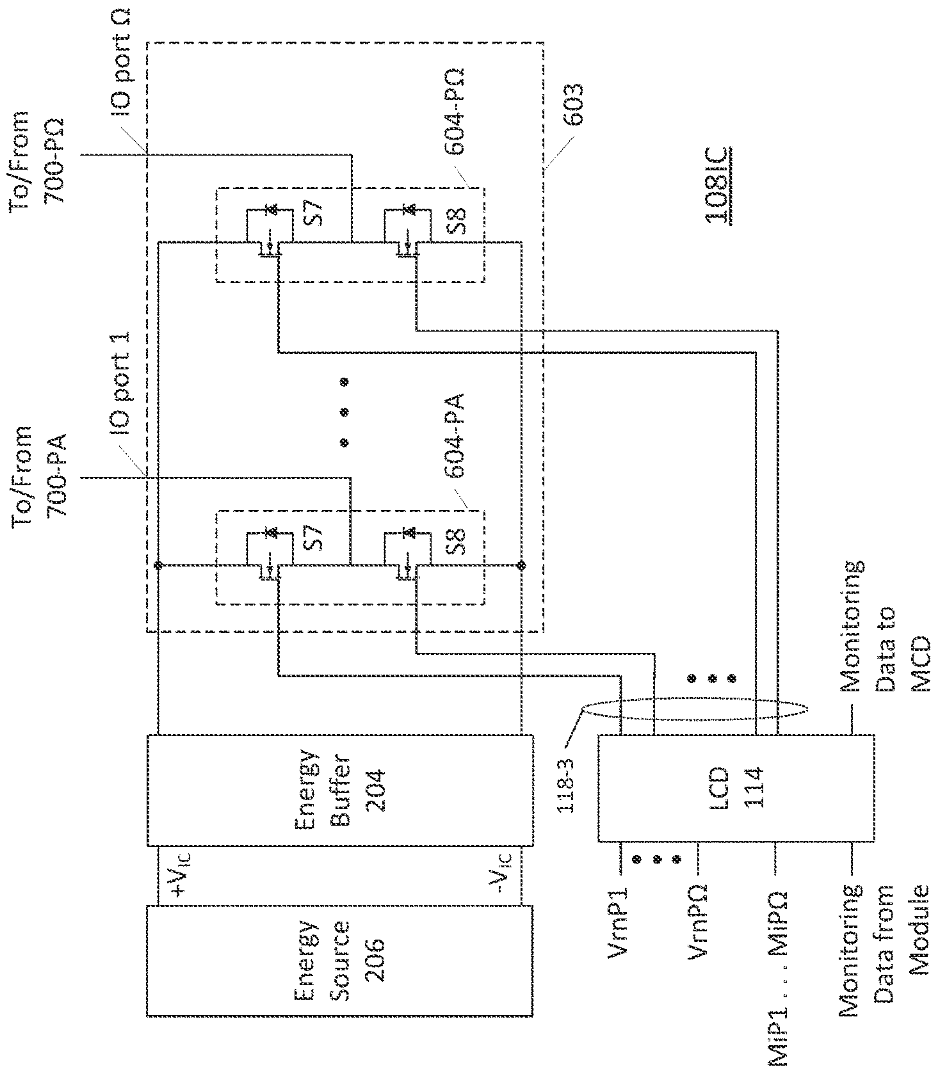


FIG. 10B

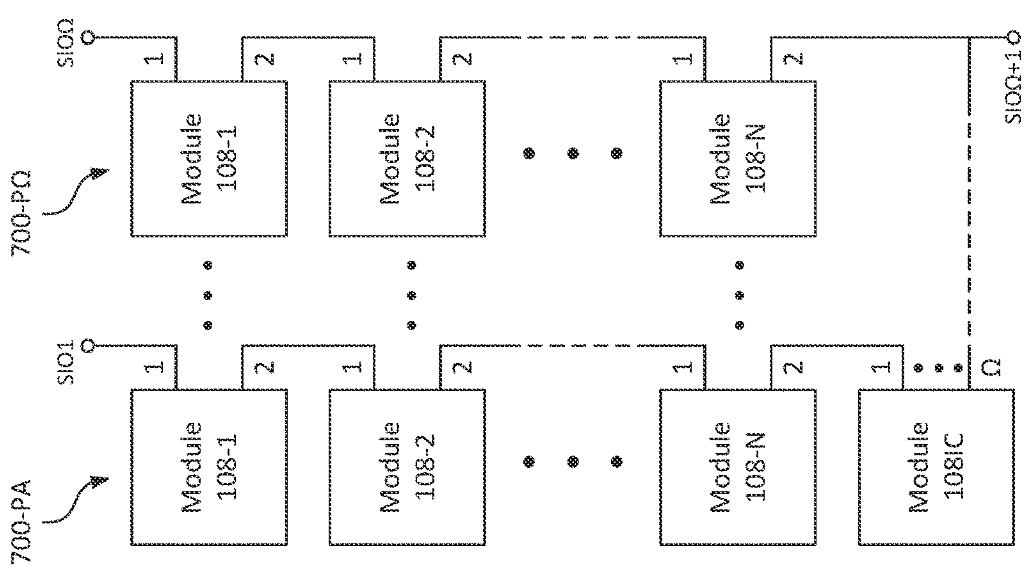


FIG. 10A

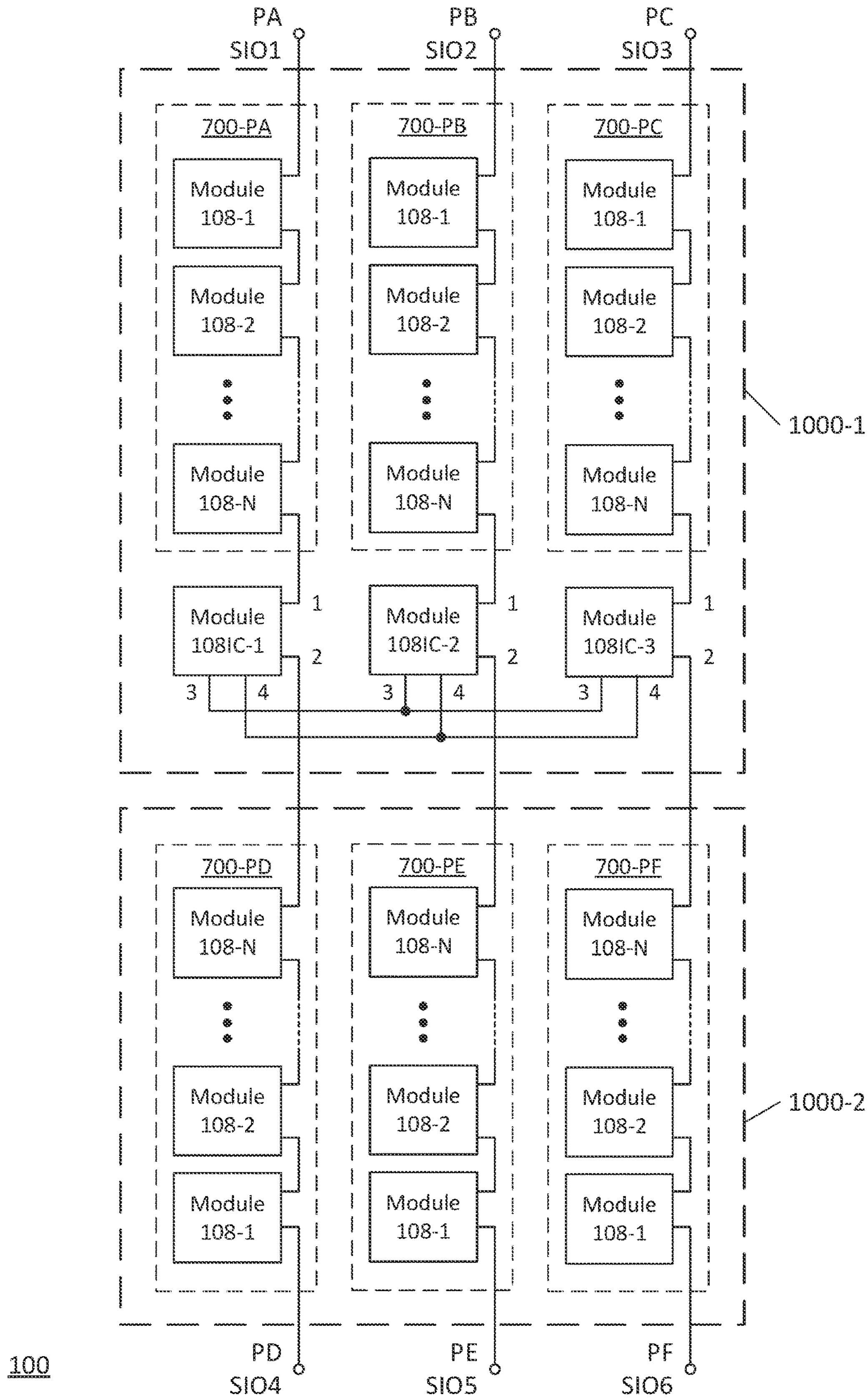
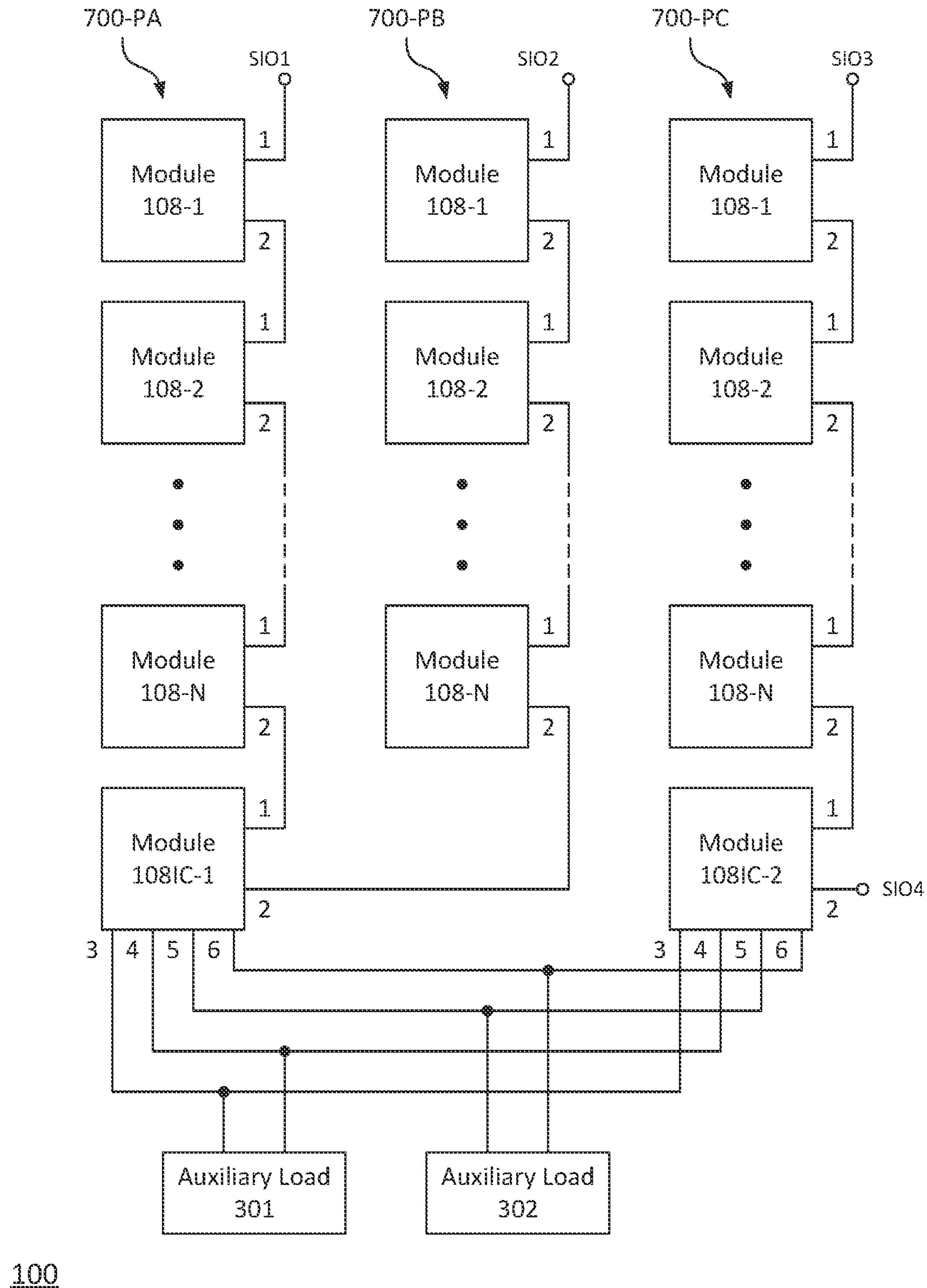

PA
SIO1
PB
SIO2
PC
SIO3
700-PA
700-PB
700-PC
Module 108-1
Module 108-2
Module 108-N
1000-1
Module 108IC-1
Module 108IC-2
Module 108IC-3
1
2
3
4
700-PD
700-PE
700-PF
Module 108-N
Module 108-2
Module 108-1
1000-2
PD
SIO4
PE
SIO5
PF
SIO6
100

FIG. 10C



700-PA
700-PB
700-PC
SIO1
SIO2
SIO3
SIO4
Module 108-1
Module 108-2
Module 108-N
Module 108IC-1
Module 108IC-2
1
2
3
4
5
6
Auxiliary Load 301
Auxiliary Load 302
100

FIG. 10D

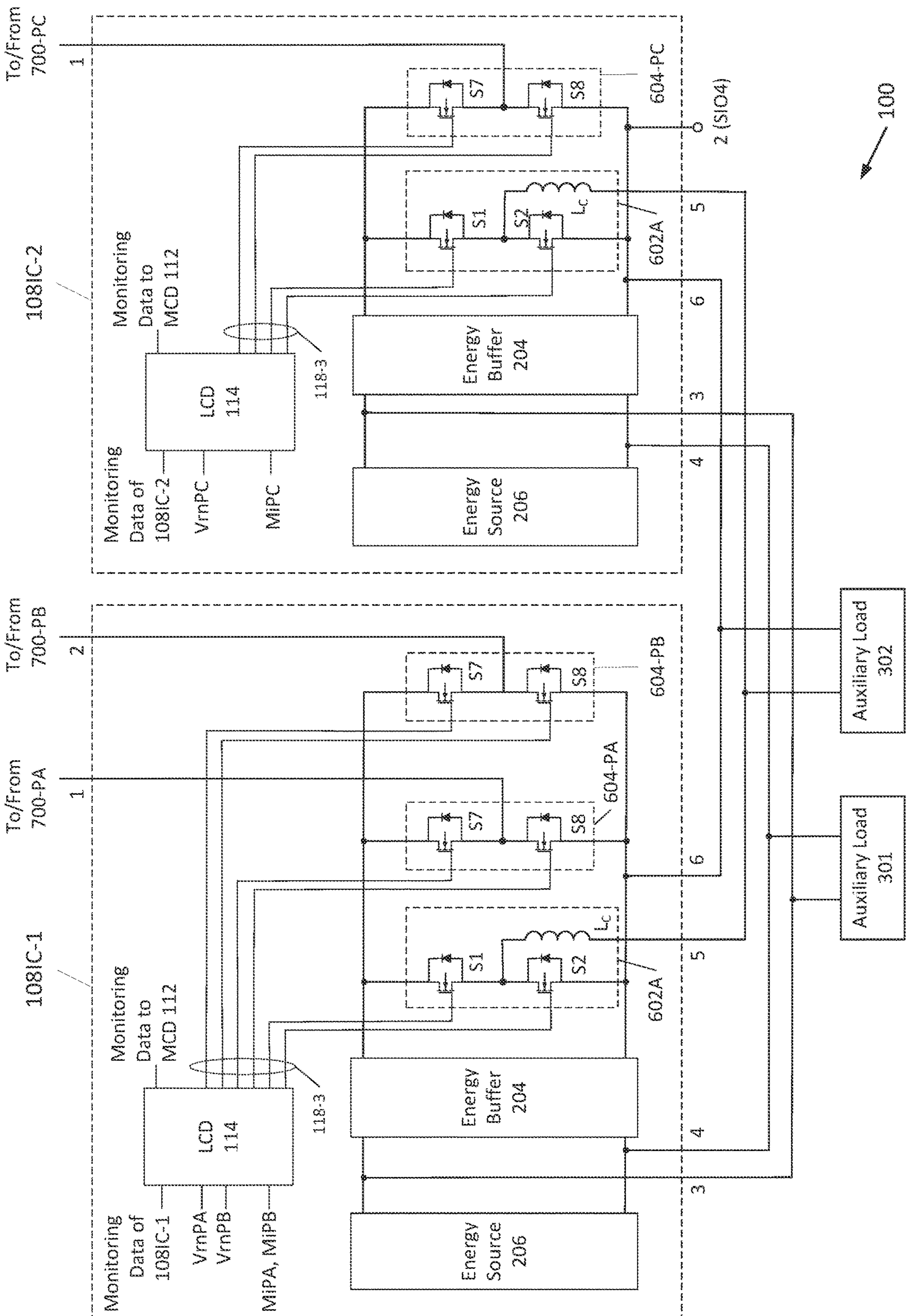

To/From 700-PC
1
108IC-2
Monitoring Data to MCD 112
LCD 114
118-3
Monitoring Data of 108IC-2
VrnPC
MIPC
Energy Buffer 204
Energy Source 206
S7
S8
604-PC
2 (SIO4)
S1
S2
L_C
602A
5
6
3
4
100
To/From 700-PB
2
To/From 700-PA
1
604-PB
604-PA
108IC-1
Monitoring Data of 108IC-1
VrnPA
VrnPB
MIPA, MIPB
Auxiliary Load 302
Auxiliary Load 301

FIG. 10E

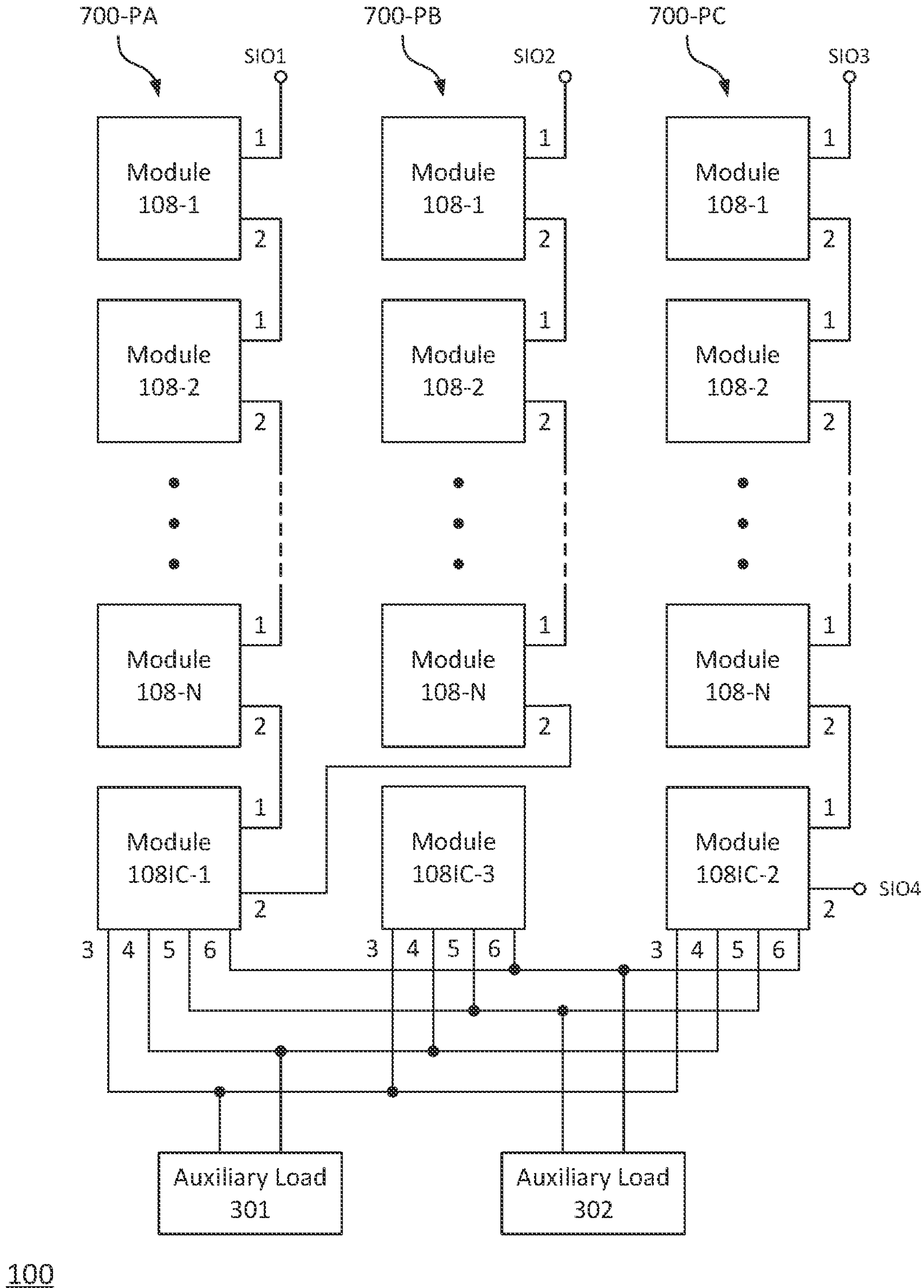

700-PA
700-PB
700-PC
SIO1
SIO2
SIO3
Module 108-1
Module 108-2
Module 108-N
Module 108IC-1
Module 108IC-3
Module 108IC-2
SIO4
1
2
3
4
5
6
Auxiliary Load 301
Auxiliary Load 302
100

FIG. 10F

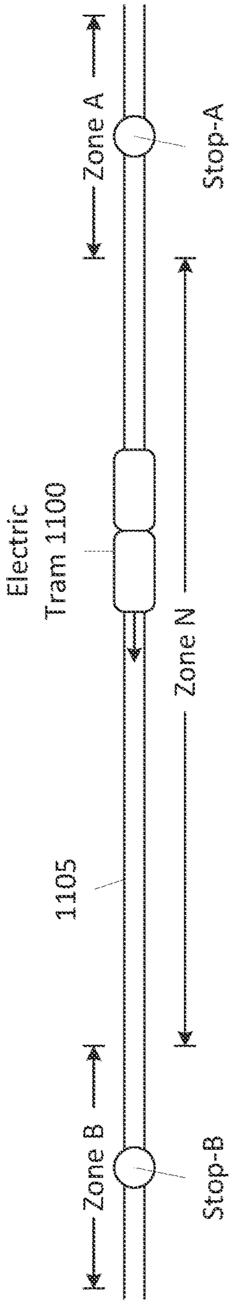


FIG. 11A

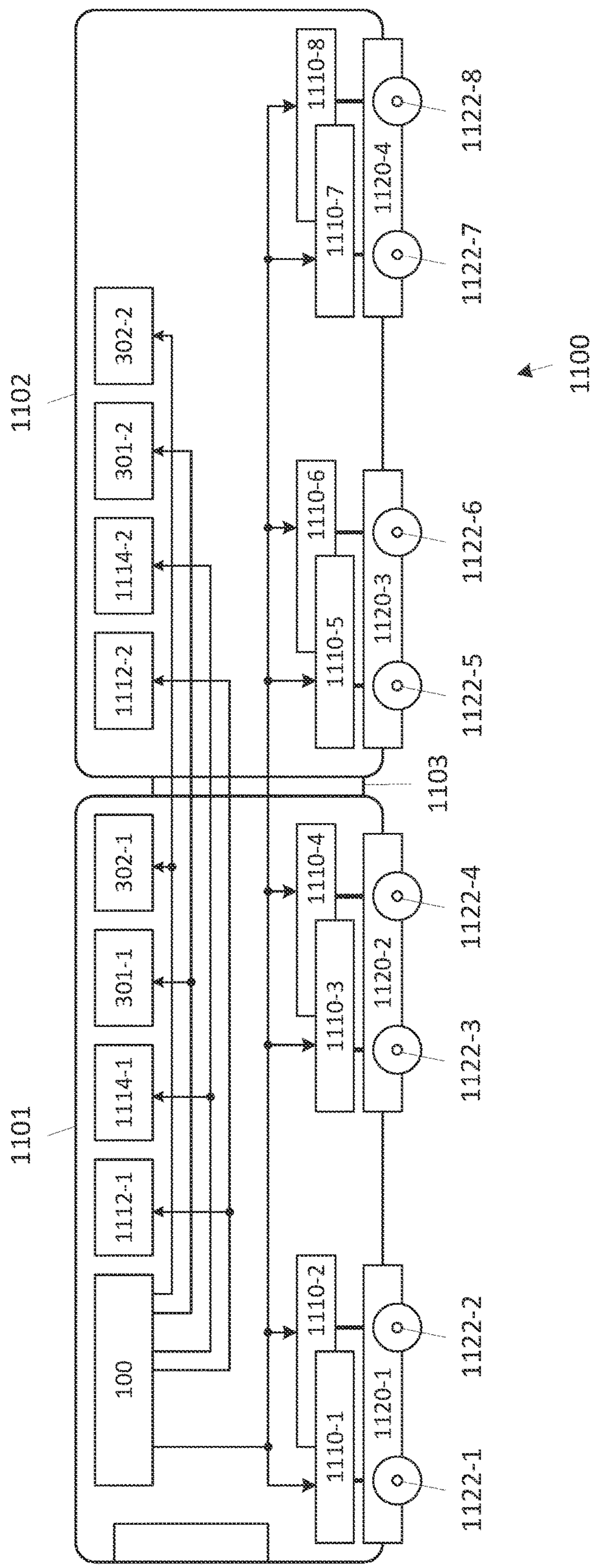


FIG. 11C

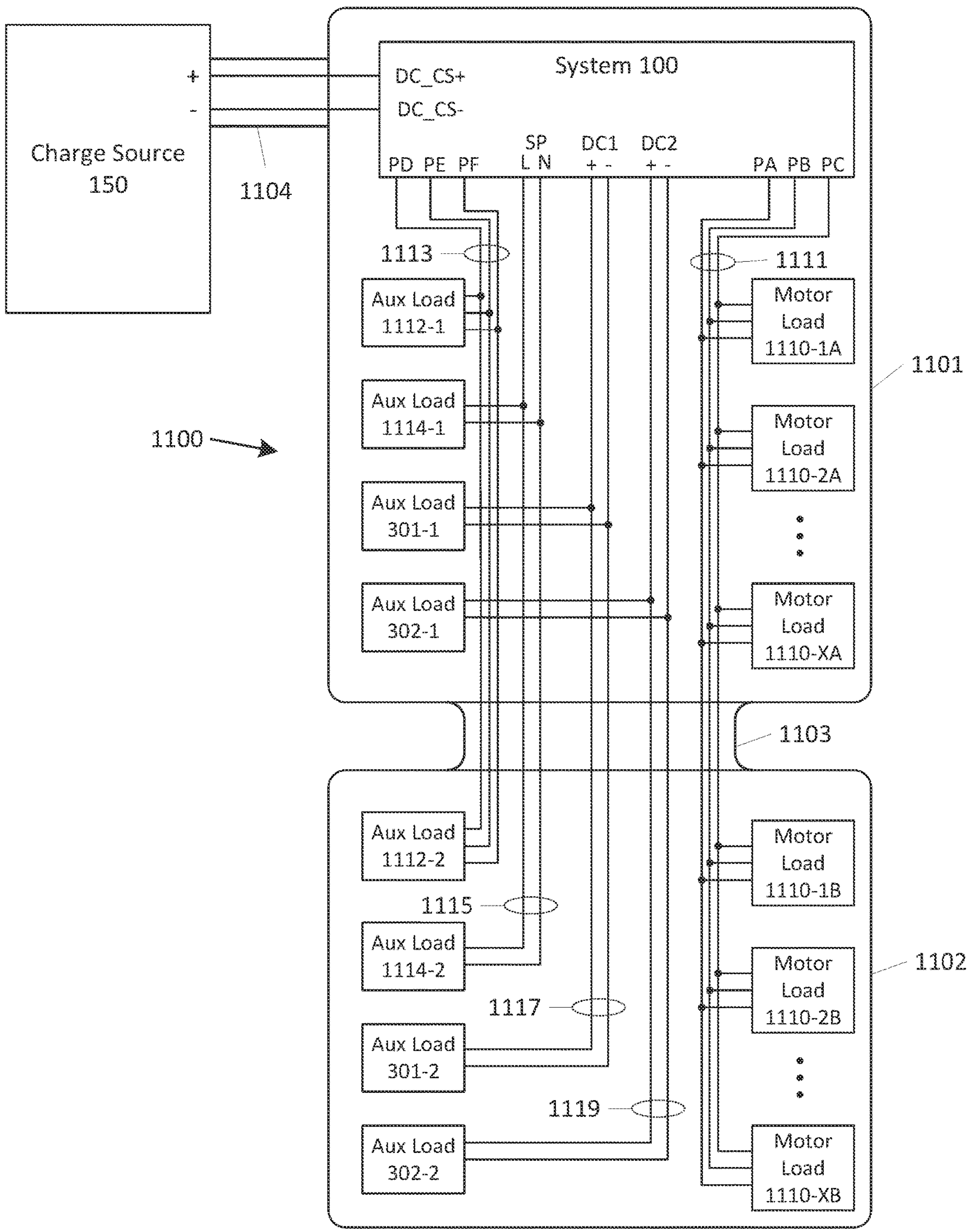

Charge Source
150
+
-
1104
System 100
DC_CS+
DC_CS-
PD PE PF
SP
L N
DC1
+ -
DC2
+ -
PA PB PC
1113
1111
Aux Load
1112-1
Aux Load
1114-1
Aux Load
301-1
Aux Load
302-1
Motor
Load
1110-1A
Motor
Load
1110-2A
Motor
Load
1110-XA
1101
1100
1103
Aux Load
1112-2
1115
Aux Load
1114-2
1117
Aux Load
301-2
1119
Aux Load
302-2
Motor
Load
1110-1B
Motor
Load
1110-2B
Motor
Load
1110-XB
1102

FIG. 11B

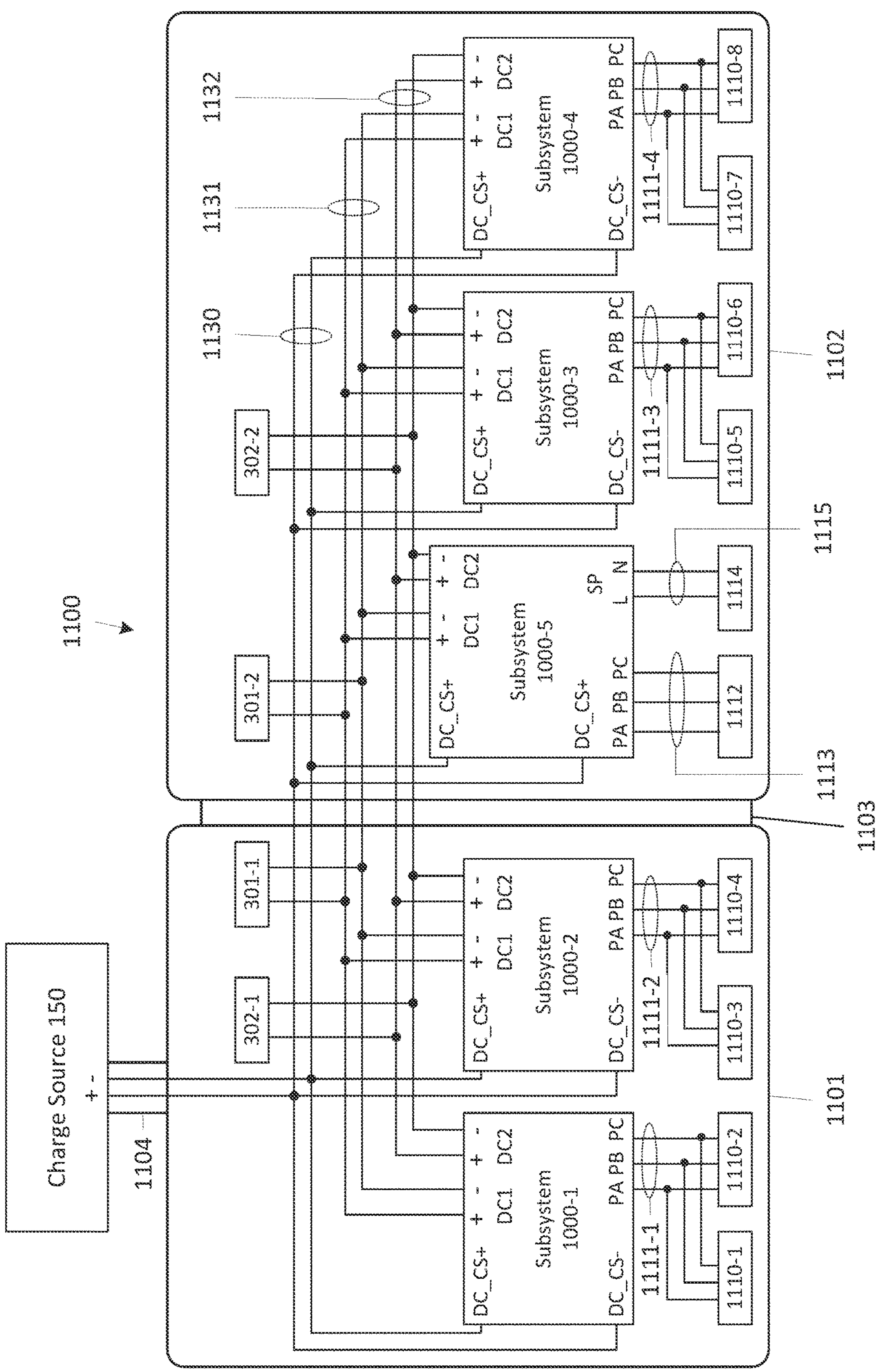

1100
Charge Source 150
+ -
1104
1101
1102
1103
Subsystem 1000-1
Subsystem 1000-2
Subsystem 1000-3
Subsystem 1000-4
Subsystem 1000-5
DC_CS+
DC_CS-
DC1
DC2
PA PB PC
SP
L N
301-1
302-1
301-2
302-2
1110-1
1110-2
1110-3
1110-4
1110-5
1110-6
1110-7
1110-8
1111-1
1111-2
1111-3
1111-4
1112
1113
1114
1115
1130
1131
1132

FIG. 11D

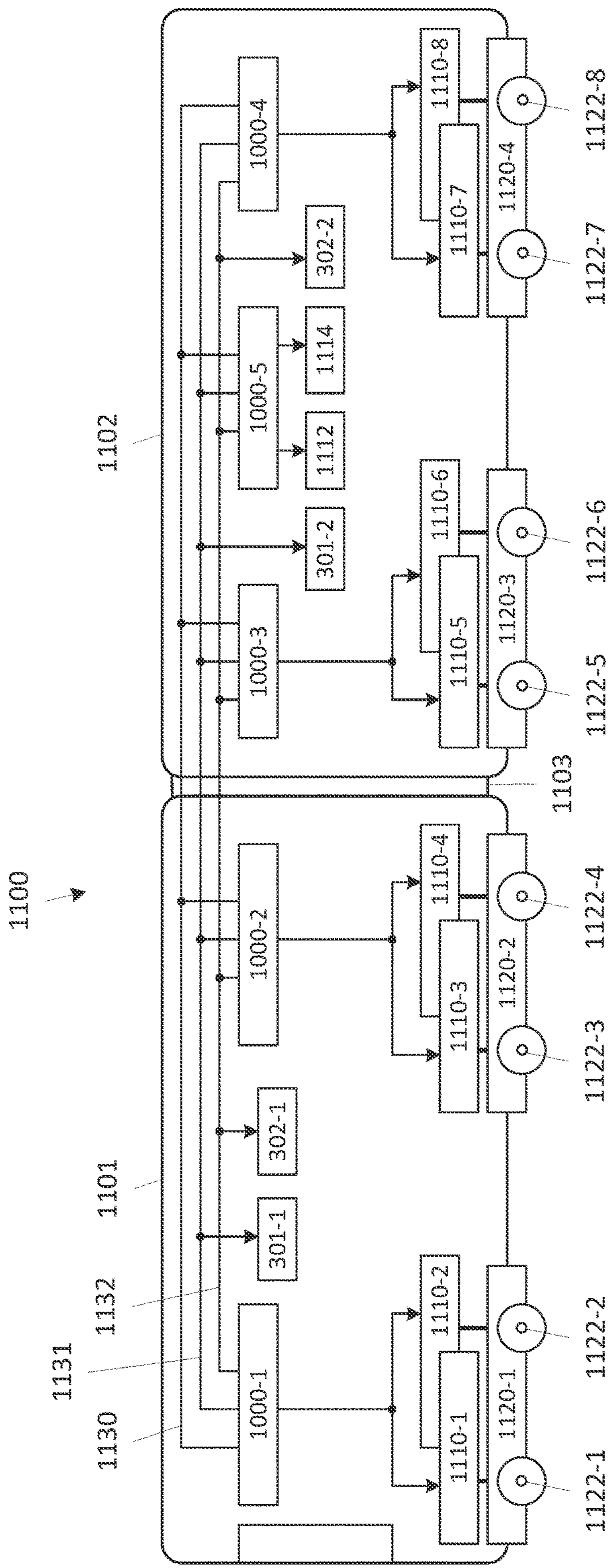

1100
1101
1102
1103
1130
1131
1132
1000-1
1000-2
1000-3
1000-4
1000-5
301-1
302-1
301-2
302-2
1112
1114
1110-1
1110-2
1110-3
1110-4
1110-5
1110-6
1110-7
1110-8
1120-1
1120-2
1120-3
1120-4
1122-1
1122-2
1122-3
1122-4
1122-5
1122-6
1122-7
1122-8

FIG. 11E

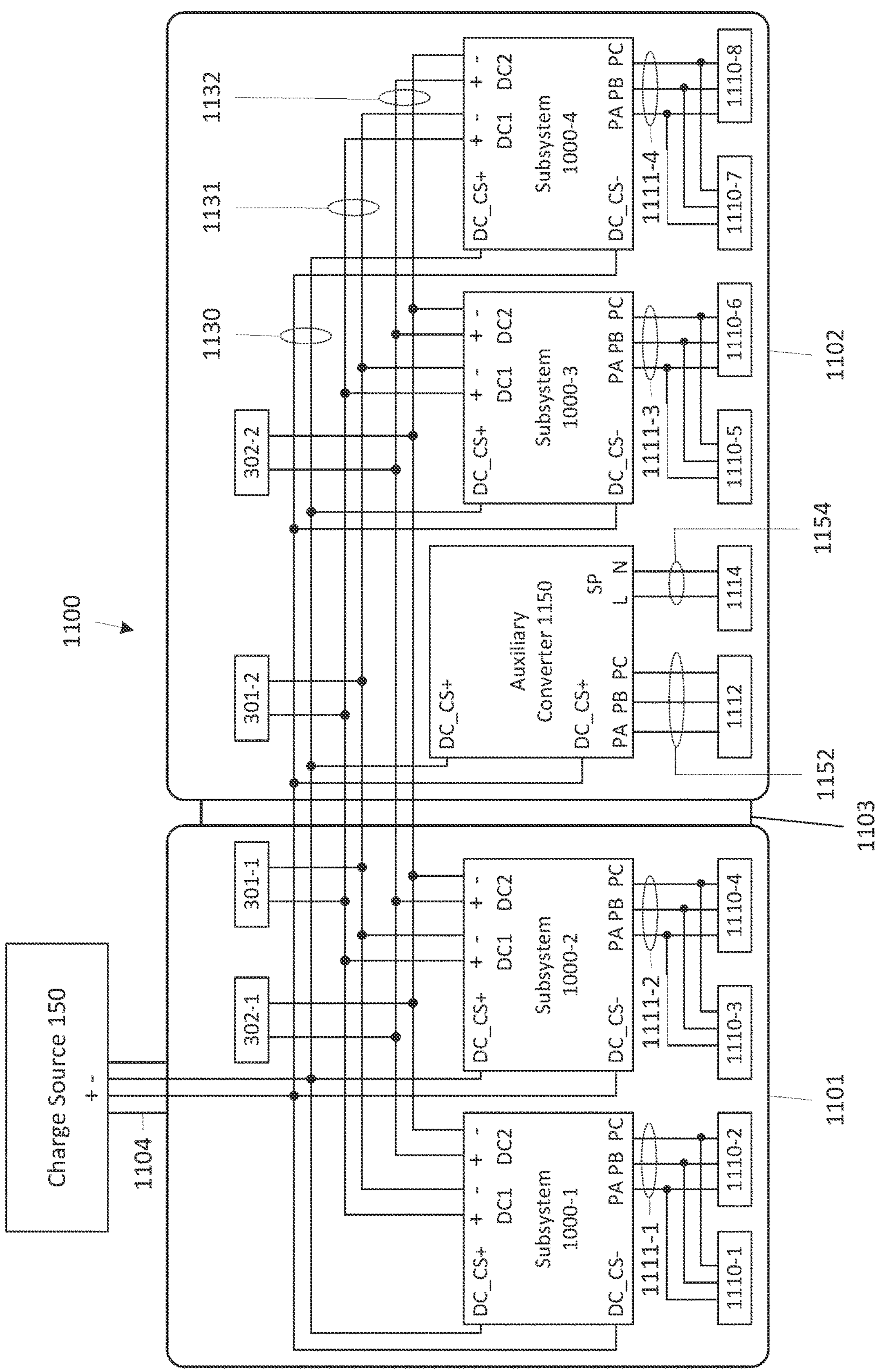

1100
Charge Source 150
+ -
1104
1101
1102
1103
1130
1131
1132
1152
1154
301-1
302-1
301-2
302-2
Subsystem 1000-1
Subsystem 1000-2
Subsystem 1000-3
Subsystem 1000-4
DC_CS+
DC_CS-
DC1
DC2
PA PB PC
1111-1
1111-2
1111-3
1111-4
1110-1
1110-2
1110-3
1110-4
1110-5
1110-6
1110-7
1110-8
Auxiliary Converter 1150
SP
L_N
1112
1114

FIG. 11F

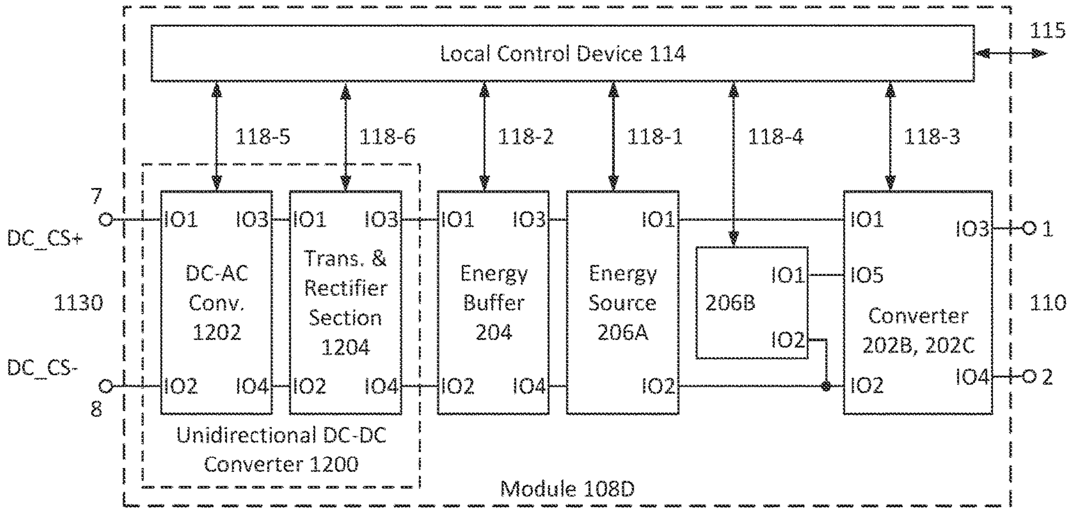


FIG. 12A

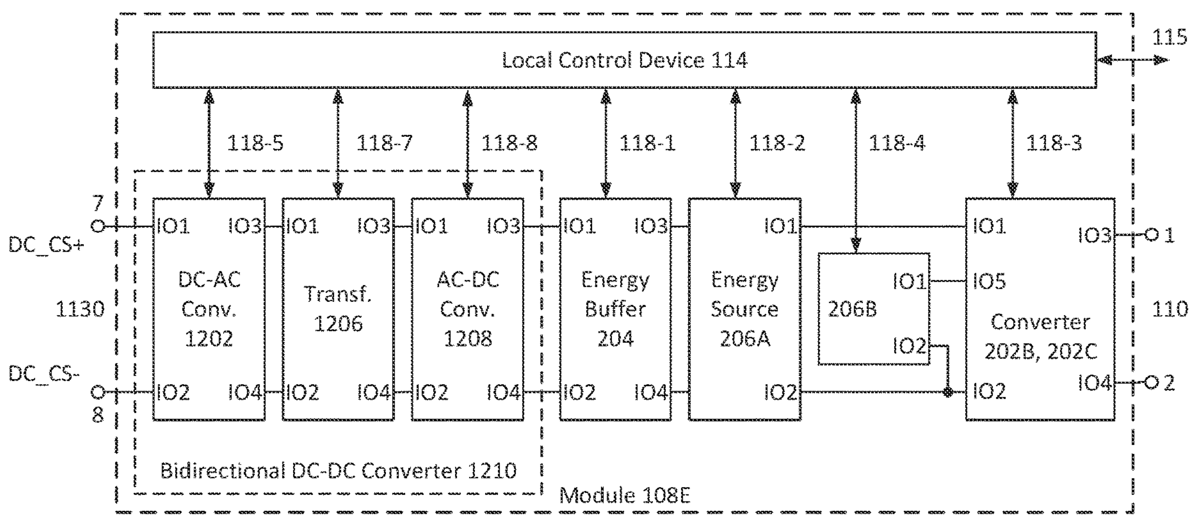


FIG. 12B

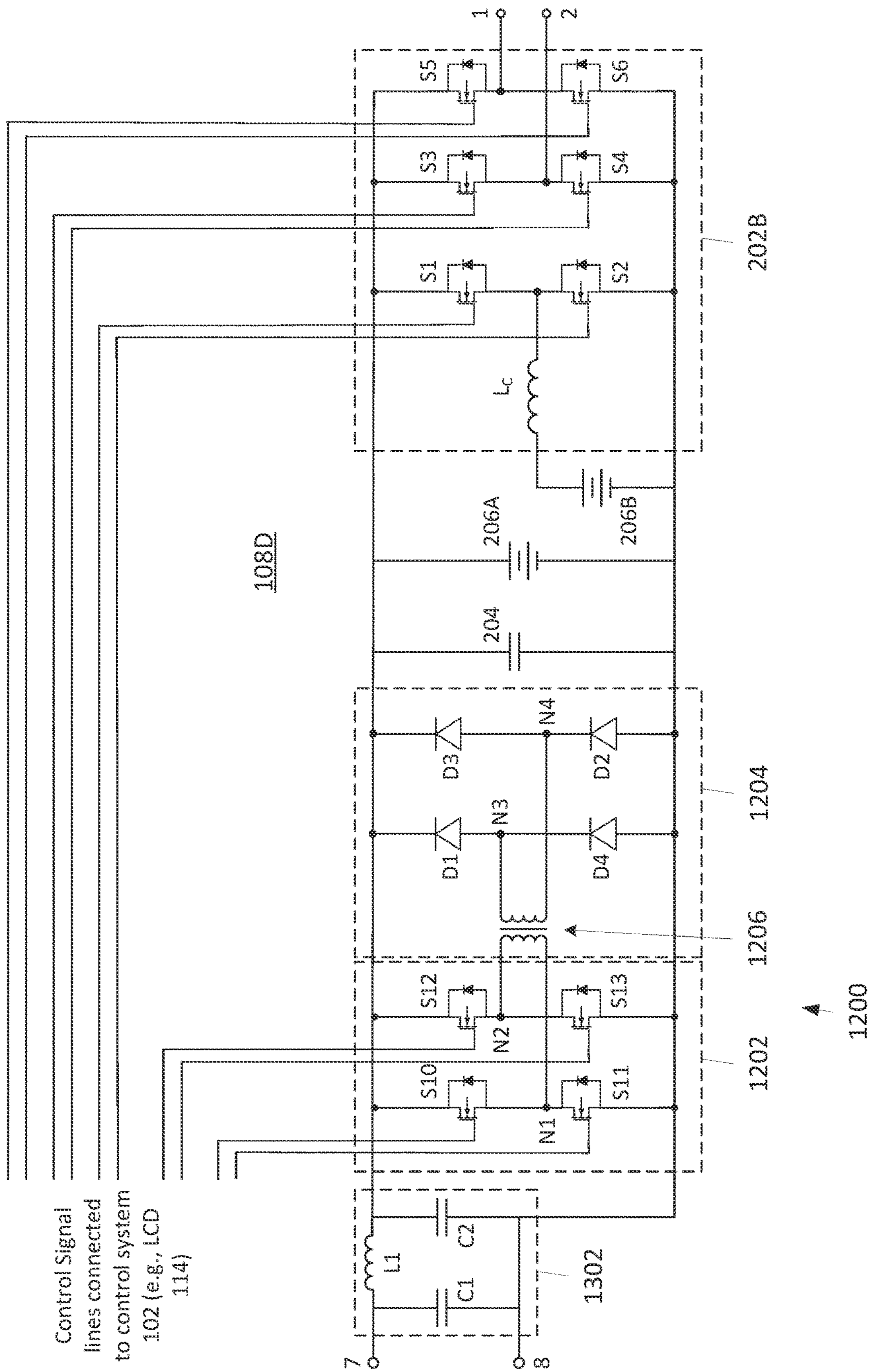
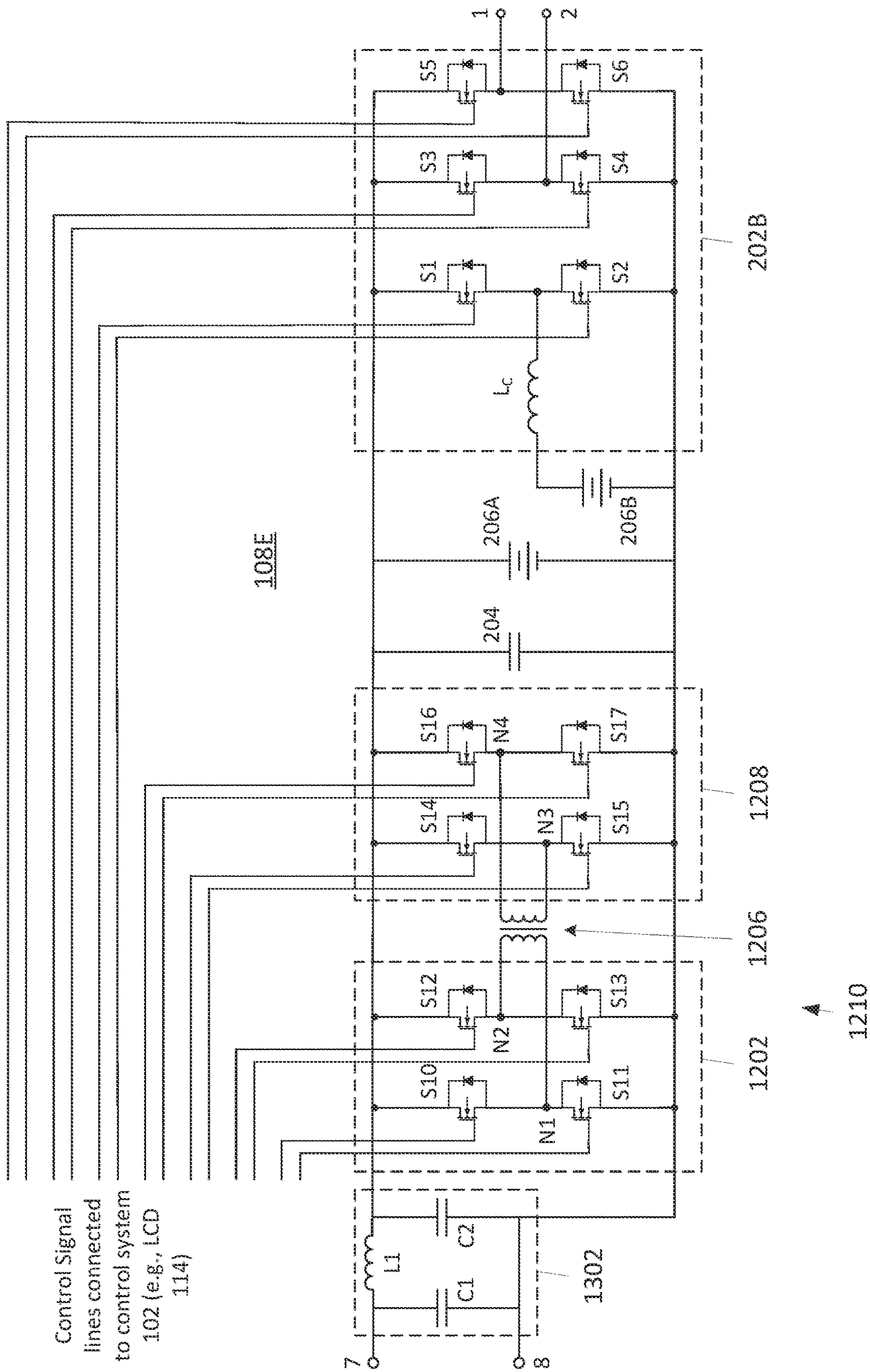

1
2
S5
S6
S3
S4
S1
S2
202B
L_C
206A
206B
108D
204
D3
N4
D2
D1
N3
D4
1204
1206
S12
S13
N2
S10
S11
N1
1202
1200
Control Signal lines connected to control system 102 (e.g., LCD 114)
L1
C2
C1
1302
7
8

FIG. 13A



1
2
S5
S6
S3
S4
S1
S2
202B
L_C
206A
206B
204
108E
S16
N4
S17
S14
N3
S15
1208
1206
S12
S13
S10
S11
N2
N1
1202
1210
L1
C1
C2
1302
7
8
Control Signal lines connected to control system 102 (e.g., LCD 114)

FIG. 13B

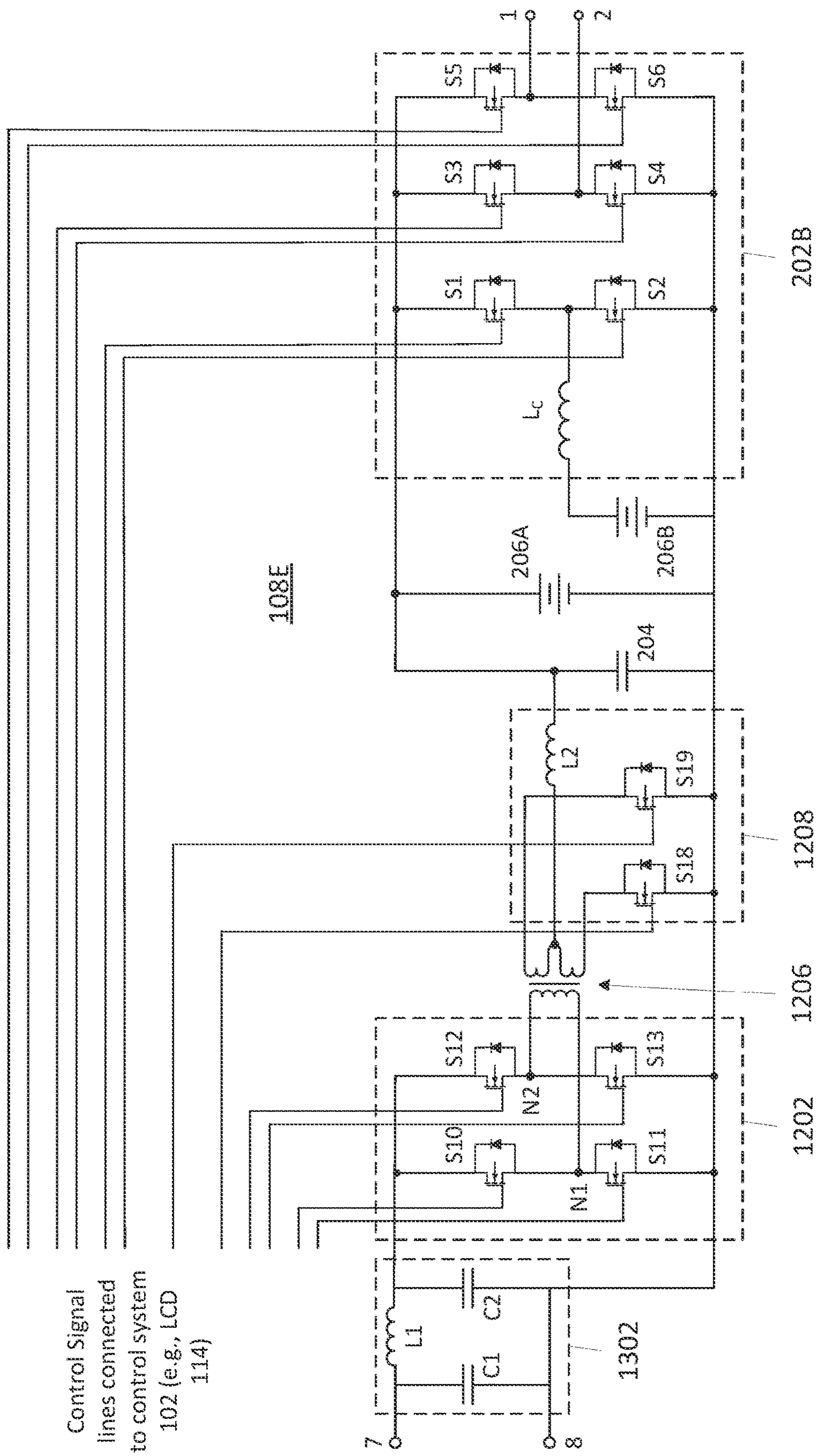

1
2
S5
S6
S3
S4
S1
S2
202B
L_C
206A
206B
108E
204
L2
S19
S18
1208
1206
S12
S13
N2
S10
S11
N1
1202
L1
C1
C2
1302
7
8
Control Signal lines connected to control system 102 (e.g., LCD 114)

FIG. 13C

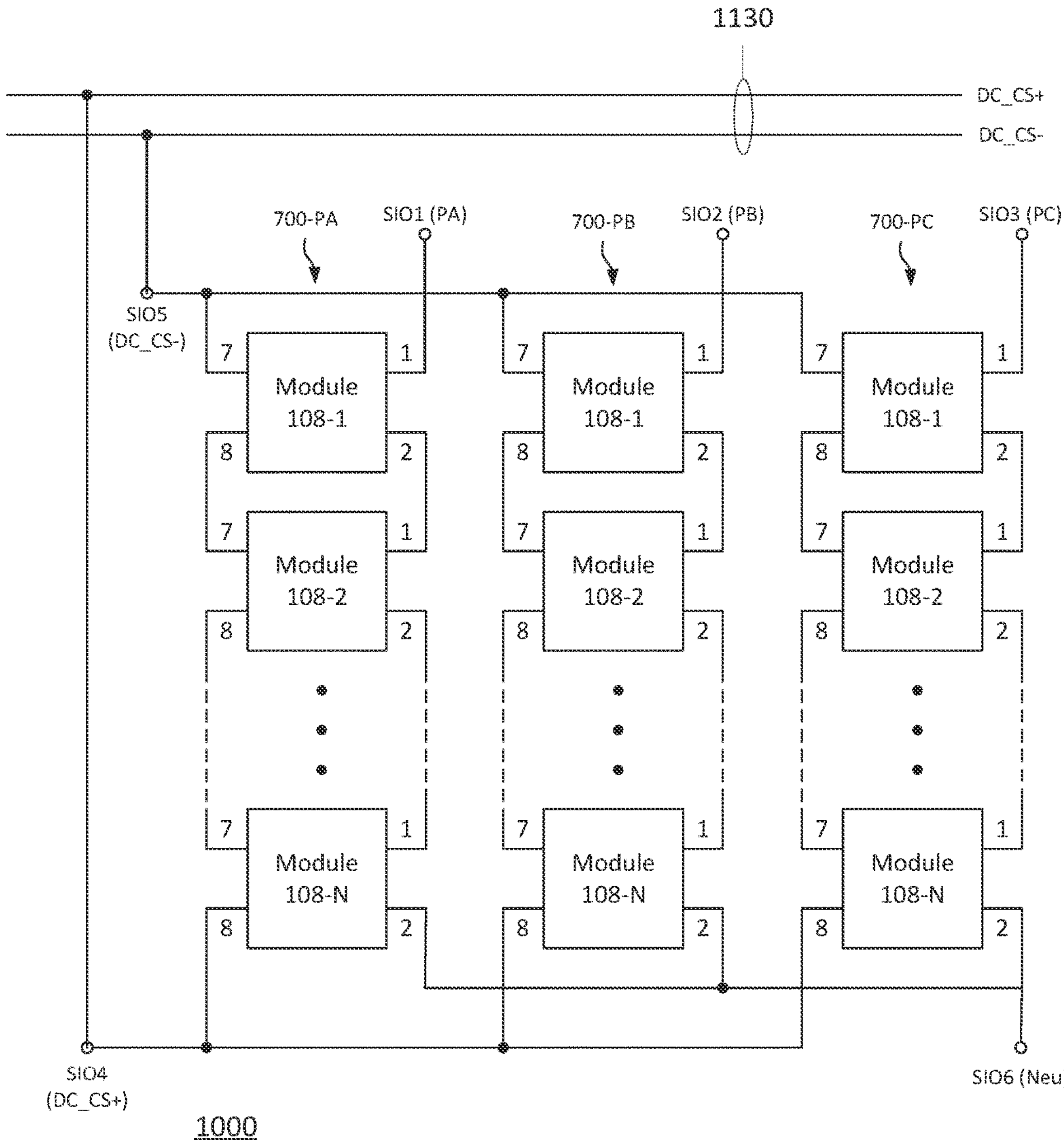
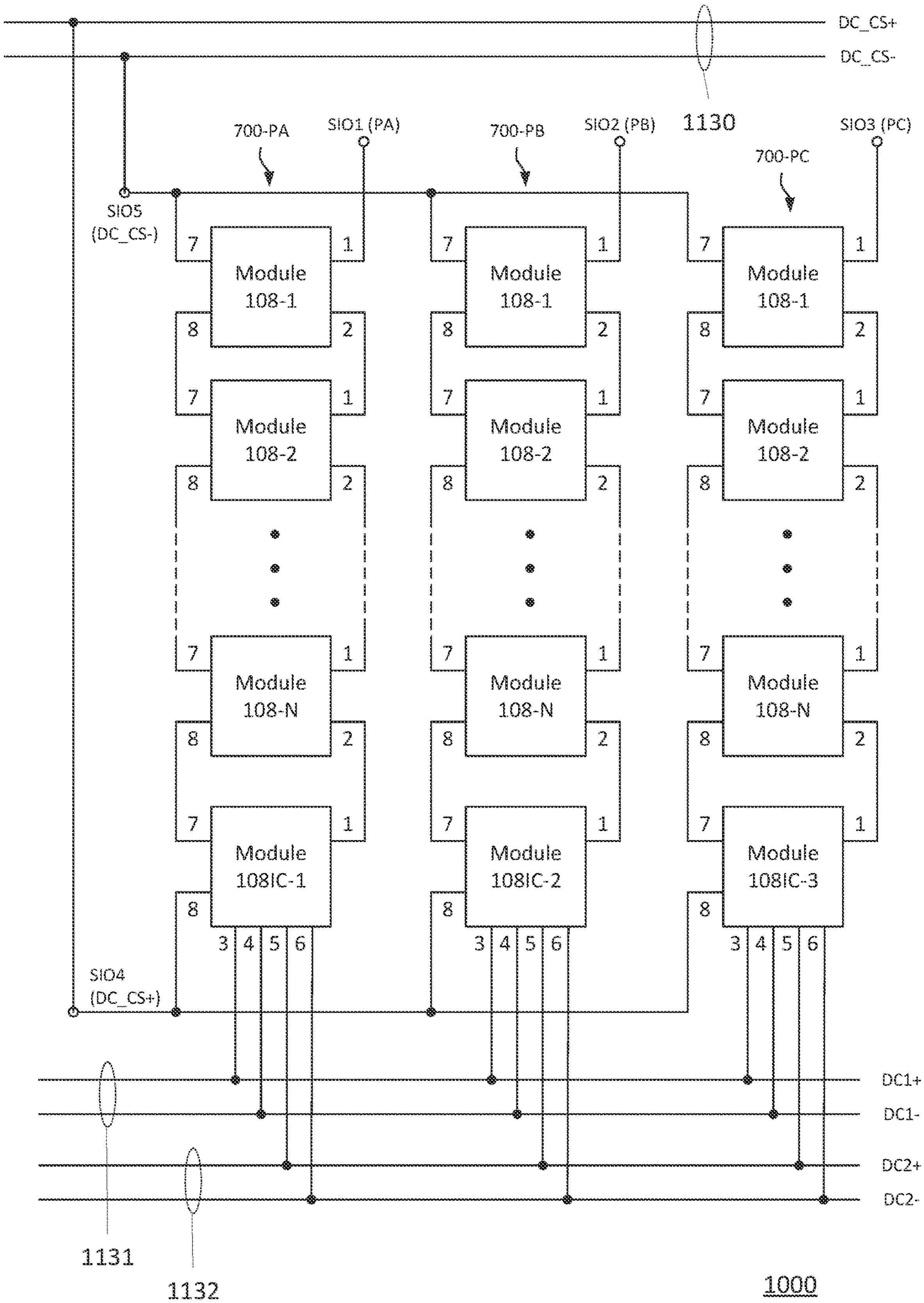

1130
DC_CS+
DC_CS-
700-PA
SIO1 (PA)
700-PB
SIO2 (PB)
700-PC
SIO3 (PC)
SIO5
(DC_CS-)
Module
108-1
Module
108-2
Module
108-N
SIO4
(DC_CS+)
SIO6 (Neu)
1000

FIG. 14A



DC_CS+
DC_CS-
1130
700-PA
SIO1 (PA)
700-PB
SIO2 (PB)
SIO3 (PC)
700-PC
SIO5
(DC_CS-)
Module
108-1
Module
108-2
Module
108-N
Module
108IC-1
Module
108IC-2
Module
108IC-3
1
2
3
4
5
6
7
8
SIO4
(DC_CS+)
DC1+
DC1-
DC2+
DC2-
1131
1132
1000

FIG. 14B

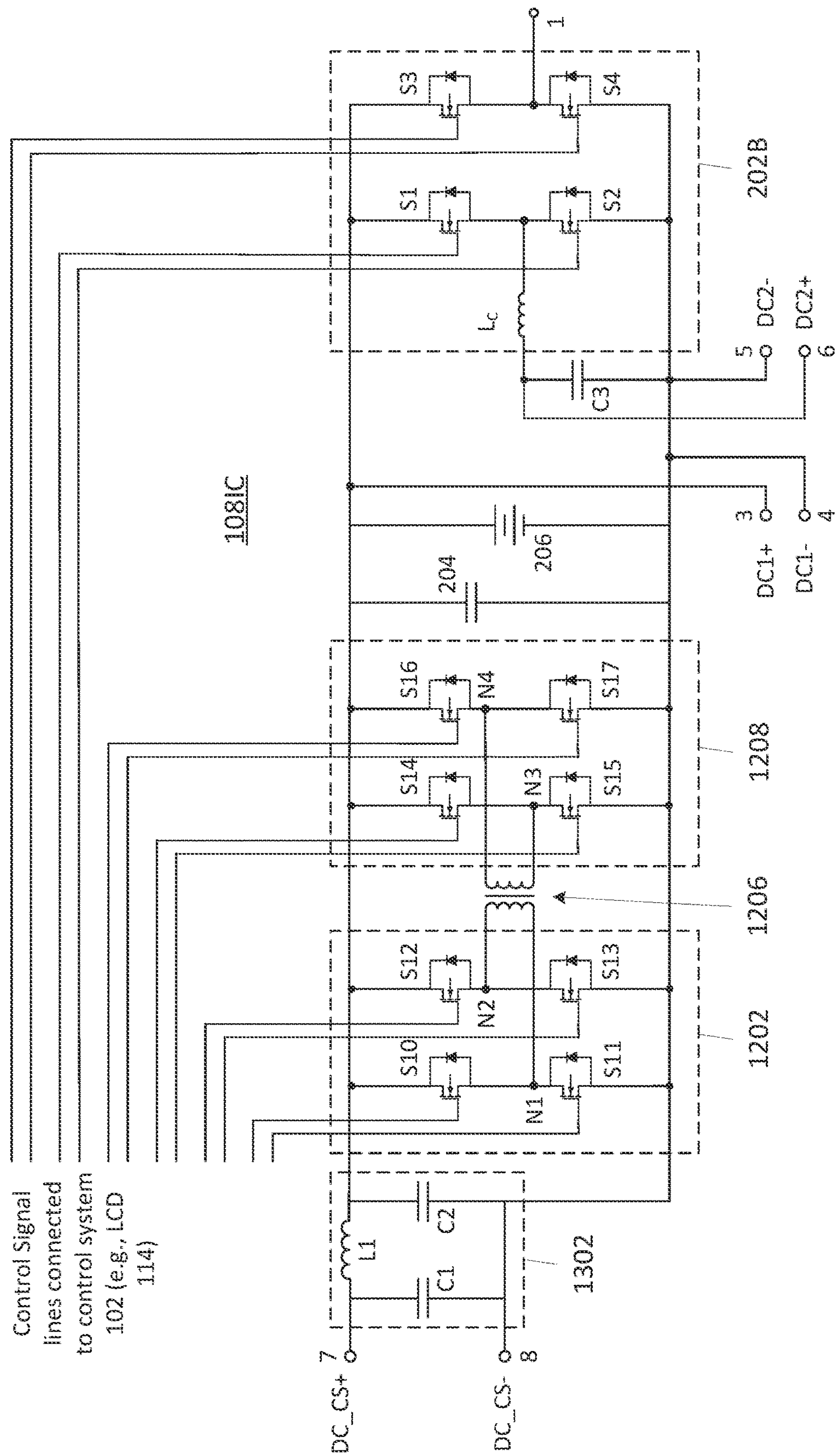

1
S3
S4
S1
S2
202B
L_C
DC2-
DC2+
5
6
C3
108IC
3
4
DC1+
DC1-
206
204
S16
S17
N4
S14
S15
N3
1208
1206
S12
S13
N2
S10
S11
N1
1202
C2
L1
C1
1302
Control Signal lines connected to control system 102 (e.g., LCD 114)
7
8
DC_CS+
DC_CS-

FIG. 14C

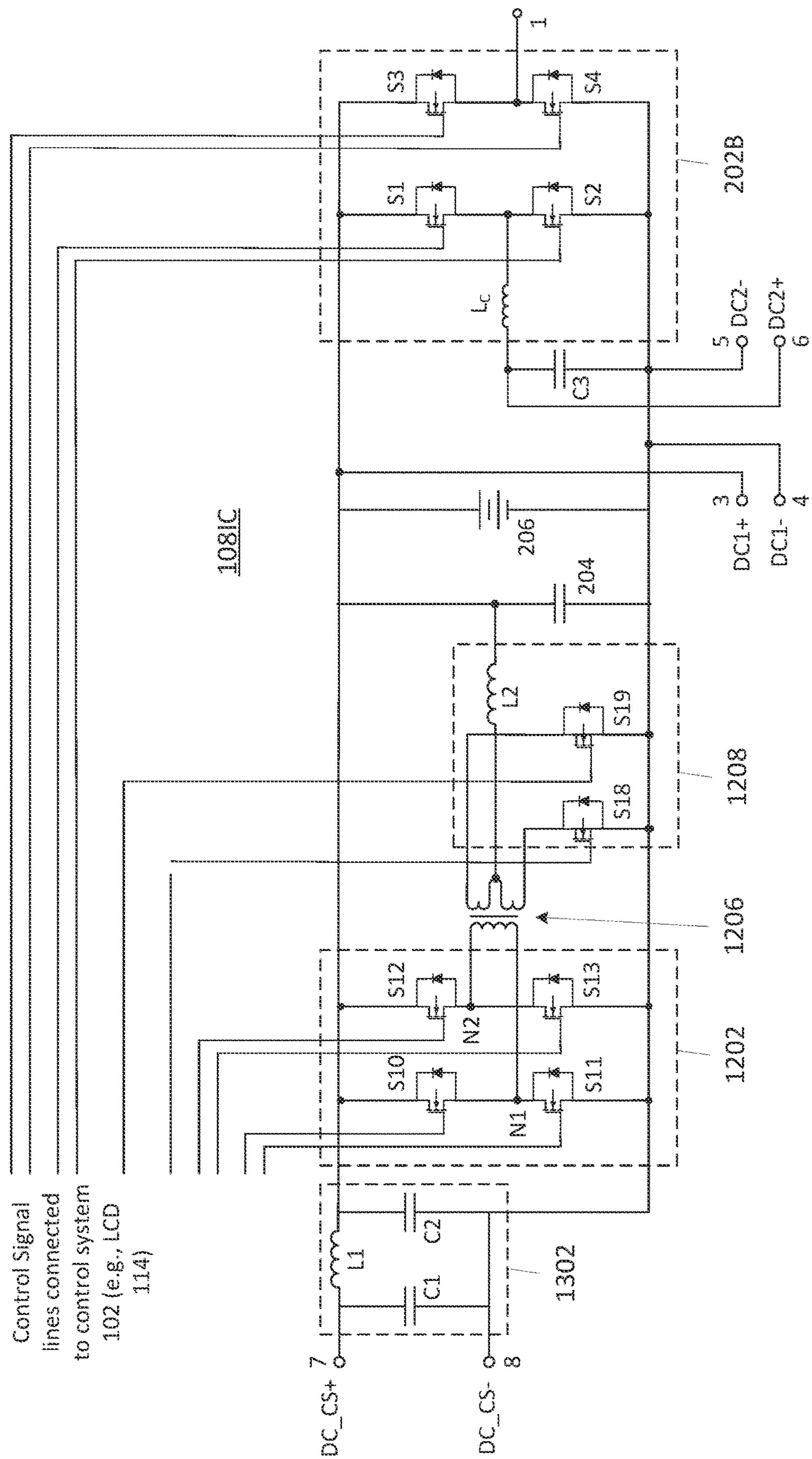

1
S3
S4
S1
S2
202B
Lc
DC2-
5
DC2+
6
C3
3
DC1+
4
DC1-
206
204
108IC
L2
S19
S18
1208
1206
S12
S13
S10
S11
N2
N1
1202
C2
C1
L1
1302
Control Signal lines connected to control system 102 (e.g., LCD 114)
7
DC_CS+
8
DC_CS-

FIG. 14D

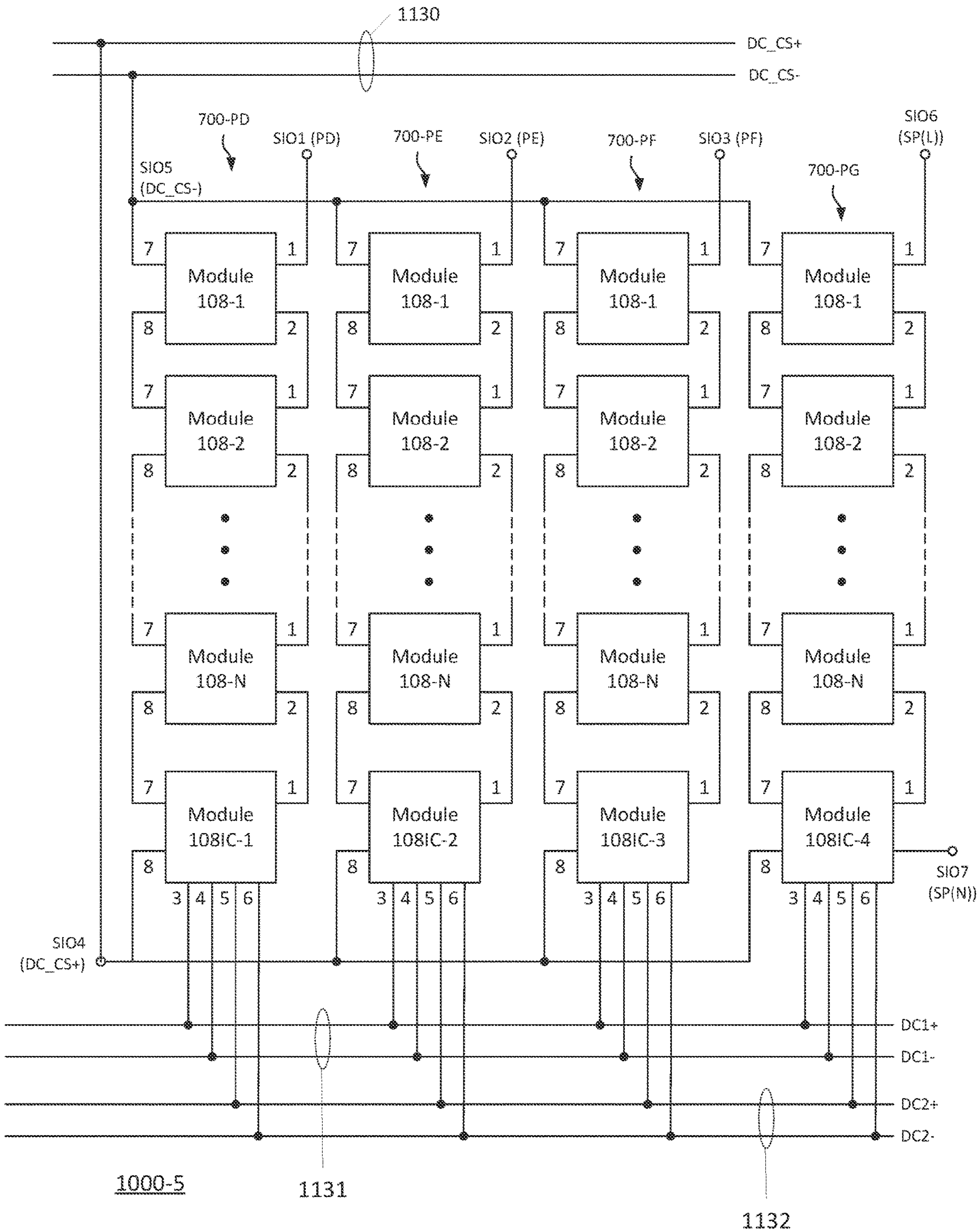

1130
DC_CS+
DC_CS-
700-PD
SIO1 (PD)
700-PE
SIO2 (PE)
700-PF
SIO3 (PF)
SIO6
(SP(L))
700-PG
SIO5
(DC_CS-)
Module
108-1
Module
108-2
Module
108-N
Module
108IC-1
Module
108IC-2
Module
108IC-3
Module
108IC-4
SIO7
(SP(N))
SIO4
(DC_CS+)
DC1+
DC1-
DC2+
DC2-
1000-5
1131
1132

FIG. 15

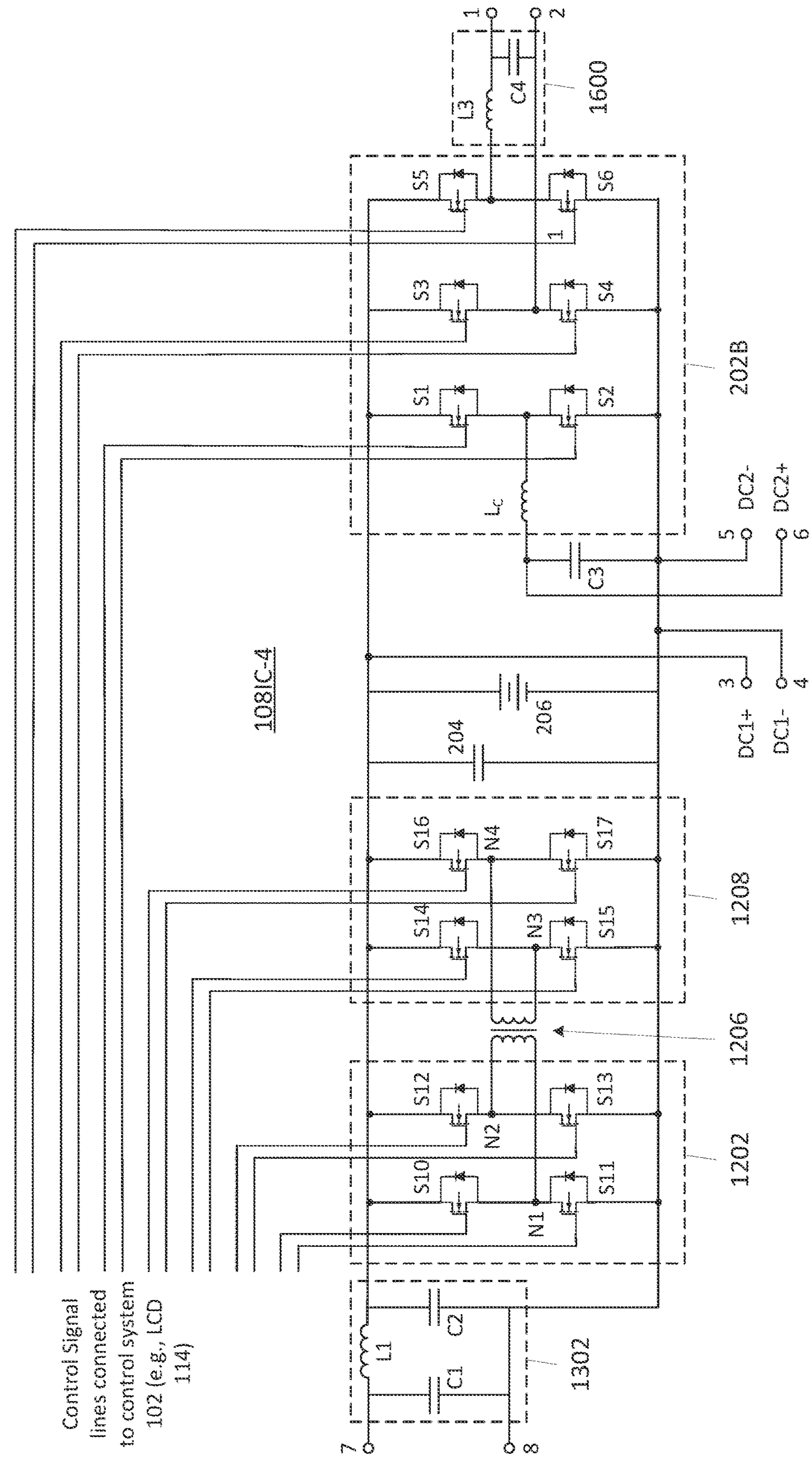

1
2
L3
C4
1600
S5
S6
S3
S4
S1
S2
202B
L_c
C3
5
6
DC2-
DC2+
108IC-4
3
4
DC1+
DC1-
206
204
S16
S17
S14
S15
N4
N3
1208
1206
S12
S13
S10
S11
N2
N1
1202
L1
C1
C2
1302
7
8
Control Signal lines connected to control system 102 (e.g., LCD 114)

FIG. 16

SYSTEMS, DEVICES, AND METHODS FOR RAIL-BASED AND OTHER ELECTRIC VEHICLES WITH MODULAR CASCADED ENERGY SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

This patent application is a continuation (and claims the benefit of priority under 35 USC 120) of U.S. patent application Ser. No. 17/319,947, filed May 13, 2021, which claims the benefit of, and priority to, U.S. Provisional Application No. 63/025,099, filed May 14, 2020, U.S. Provisional Application No. 63/029,368, filed May 22, 2020, and U.S. Provisional Application No. 63/084,293, filed Sep. 28, 2020, all of which are incorporated by reference herein in their entireties and for all purposes.

FIELD

The subject matter described herein relates generally to systems, devices, and methods for rail-based and other electric vehicles having modular cascaded energy systems.

BACKGROUND

For electric vehicles that operate on a rail, power to drive the electric motors is provided by a charge source. This charge source is typically in the form of a high-voltage conductor that is present along a span of track. The charge source can be an overhead line, such as a catenary, a ground-level power supply such as third rail, or a below-ground supplies such as a conduit. The rail-based EV receives power from this charge source by means of a conductive element (e.g., a pantograph or plow) that remains in continuous contact with the charge source as the EV is moving. In some cases, the rail-based EV uses a static approach and extends a conductor into contact with the charge source when the vehicle is at rest, charges while the vehicle is not moving, and withdraws the conductor from contact with the charge source prior to resuming movement.

Charge source lines that run continually alongside the rail require additional physical space and infrastructure, can be unaesthetic, can pose risks to the public in the environment, and our costly to build and maintain in a safe manner. Conventional rail-based EVs can be configured with an energy storage system that stores power for operating the motors and allows the rail-based EV to traverse spans of rail where no charge source is present. However, these rail-based EVs can suffer from limitations in range, limitations in lifespan of the energy sources, and lack of flexibility in implementation for rail-based EVs with numerous motors and auxiliary loads requiring electric power.

As such, needs exist for improved energy systems for use in rail-based electric vehicles and related vehicles and stationary applications.

SUMMARY

Example embodiments of systems, devices, and methods are provided herein for electric vehicles that are subject to intermittent charging, such as rail-based electric vehicles, having one or more modular cascaded energy systems. The one or more modular systems can be configured to supply multiphase, single phase, and/or DC power to numerous motor and auxiliary loads of the EV. If multiple systems or subsystems are present in the EV, they can be interconnected to exchange energy between them in numerous different ways, such as through lines designated for carrying power from the intermittently connected charge source or through the presence of modules interconnected between arrays of the subsystems. The subsystems can be configured as subsystems that supply power for motor loads alone, motor loads in combination with auxiliary loads, and auxiliary loads alone.

Each module of the subsystems can be configured with multiple converters and one or more energy sources such that the modules can receive relatively high voltage signals from the intermittently connected charge source and modify that voltage with one or more converters to charge the one or more energy sources, and also such that the modules can utilize another converter two convert the DC voltage from the one or more energy sources into an AC output voltage for powering the one or more loads of the EV. The charging can occur while the EV is moving, such as with a rail-based EV receiving power from an overhead, ground-level, or below-ground charge source. The embodiments are applicable to other applications as well.

Other systems, devices, methods, features and advantages of the subject matter described herein will be or will become apparent to one with skill in the art upon examination of the following figures and detailed description. It is intended that all such additional systems, methods, features and advantages be included within this description, be within the scope of the subject matter described herein, and be protected by the accompanying claims. In no way should the features of the example embodiments be construed as limiting the appended claims, absent express recitation of those features in the claims.

BRIEF DESCRIPTION OF FIGURES

The details of the subject matter set forth herein, both as to its structure and operation, may be apparent by study of the accompanying figures, in which like reference numerals refer to like parts. The components in the figures are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the subject matter. Moreover, all illustrations are intended to convey concepts, where relative sizes, shapes and other detailed attributes may be illustrated schematically rather than literally or precisely.

FIGS. **1A-1C** are block diagrams depicting example embodiments of a modular energy system.

FIGS. **1D-1E** are block diagrams depicting example embodiments of control devices for an energy system.

FIGS. **1F-1G** are block diagrams depicting example embodiments of modular energy systems coupled with a load and a charge source.

FIGS. **2A-2B** are block diagrams depicting example embodiments of a module and control system within an energy system.

FIG. **2C** is a block diagram depicting an example embodiment of a physical configuration of a module.

FIG. **2D** is a block diagram depicting an example embodiment of a physical configuration of a modular energy system.

FIGS. **3A-3C** are block diagrams depicting example embodiments of modules having various electrical configurations.

FIGS. **4A-4F** are schematic views depicting example embodiments of energy sources.

FIGS. **5A-5C** are schematic views depicting example embodiments of energy buffers.

FIGS. **6**A-**6**C are schematic views depicting example embodiments of converters.

FIGS. **7**A-**7**E are block diagrams depicting example embodiments of modular energy systems having various topologies.

FIG. **8**A is a plot depicting an example output voltage of a module.

FIG. **8**B is a plot depicting an example multilevel output voltage of an array of modules.

FIG. **8**C is a plot depicting an example reference signal and carrier signals usable in a pulse width modulation control technique.

FIG. **8**D is a plot depicting example reference signals and carrier signals usable in a pulse width modulation control technique.

FIG. **8**E is a plot depicting example switch signals generated according to a pulse width modulation control technique.

FIG. **8**F as a plot depicting an example multilevel output voltage generated by superposition of output voltages from an array of modules under a pulse width modulation control technique.

FIGS. **9**A-**9**B are block diagrams depicting example embodiments of controllers for a modular energy system.

FIG. **10**A is a block diagram depicting an example embodiment of a multiphase modular energy system having interconnection module.

FIG. **10**B is a schematic diagram depicting an example embodiment of an interconnection module in the multiphase embodiment of FIG. **10**A.

FIG. **10**C is a block diagram depicting an example embodiment of a modular energy system having two subsystems connected together by interconnection modules.

FIG. **10**D is a block diagram depicting an example embodiment of a three-phase modular energy system having interconnection modules supplying auxiliary loads.

FIG. **10**E is a schematic view depicting an example embodiment of the interconnection modules in the multiphase embodiment of FIG. **10**D.

FIG. **10**F is a block diagram depicting another example embodiment of a three-phase modular energy system having interconnection modules supplying auxiliary loads.

FIG. **11**A is an illustration depicting an example route of an electric rail-based vehicle.

FIG. **11**B is a block diagram depicting an example embodiment of an electrical layout of a modular energy system for an electric rail-based vehicle.

FIG. **11**C is a side diagram depicting an example embodiment of an electrical layout of a modular energy system for an electric rail-based vehicle.

FIG. **11**D is a block diagram depicting another example embodiment of an electrical layout of a modular energy system for an electric rail-based vehicle.

FIG. **11**E is a side diagram depicting another example embodiment of an electrical layout of a modular energy system for an electric rail-based vehicle.

FIG. **11**F is a block diagram depicting another example embodiment of an electrical layout of a modular energy system for an electric rail-based vehicle.

FIGS. **12**A-**12**B are block diagrams depicting example embodiments of modules for use in a modular energy system.

FIGS. **13**A-**13**C are schematic diagrams depicting example embodiments of modules for use in a modular energy system.

FIGS. **14**A-**14**B are block diagrams depicting example embodiments of modular energy system topologies.

FIGS. **14**C-**14**D are schematic diagrams depicting example embodiments of interconnection modules for use in a modular energy system.

FIG. **15** is a block diagram depicting an example embodiment of a modular energy system topology.

FIG. **16** is a schematic diagram depicting another example embodiment of an interconnection module.

DETAILED DESCRIPTION

Before the present subject matter is described in detail, it is to be understood that this disclosure is not limited to the particular embodiments described, as such may, of course, vary. The terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting, since the scope of the present disclosure will be limited only by the appended claims.

Before describing the example embodiments pertaining to modular energy systems implemented within rail-based and other applications relying on intermittent charging, it is first useful to describe these underlying systems in greater detail. With reference to FIGS. **1**A through **10**F, the following sections describe various applications in which embodiments of the modular energy systems can be implemented, embodiments of control systems or devices for the modular energy systems, configurations of the modular energy system embodiments with respect to charging sources and loads, embodiments of individual modules, embodiments of topologies for arrangement of the modules within the systems, embodiments of control methodologies, embodiments of balancing operating characteristics of modules within the systems, and embodiments of the use of interconnection modules.

Examples of Applications

Stationary applications are those in which the modular energy system is located in a fixed location during use, although it may be capable of being transported to alternative locations when not in use. The module-based energy system resides in a static location while providing electrical energy for consumption by one or more other entities, or storing or buffering energy for later consumption. Examples of stationary applications in which the embodiments disclosed herein can be used include, but are not limited to: energy systems for use by or within one or more residential structures or locales, energy systems for use by or within one or more industrial structures or locales, energy systems for use by or within one or more commercial structures or locales, energy systems for use by or within one or more governmental structures or locales (including both military and non-military uses), energy systems for charging the mobile applications described below (e.g., a charge source or a charging station), and systems that convert solar power, wind, geothermal energy, fossil fuels, or nuclear reactions into electricity for storage. Stationary applications often supply loads such as grids and microgrids, motors, and data centers. A stationary energy system can be used in either a storage or non-storage role.

Mobile applications, sometimes referred to as traction applications, are generally ones where a module-based energy system is located on or within an entity, and stores and provides electrical energy for conversion into motive force by a motor to move or assist in moving that entity. Examples of mobile entities with which the embodiments disclosed herein can be used include, but are not limited to, electric and/or hybrid entities that move over or under land, over or under sea, above and out of contact with land or sea (e.g., flying or hovering in the air), or through outer space. Examples of mobile entities with which the embodiments disclosed herein can be used include, but are not limited to, vehicles, trains, trams, ships, vessels, aircraft, and spacecraft. Examples of mobile vehicles with which the embodiments disclosed herein can be used include, but are not limited to, those having only one wheel or track, those having only two-wheels or tracks, those having only three wheels or tracks, those having only four wheels or tracks, and those having five or more wheels or tracks. Examples of mobile entities with which the embodiments disclosed herein can be used include, but are not limited to, a car, a bus, a truck, a motorcycle, a scooter, an industrial vehicle, a mining vehicle, a flying vehicle (e.g., a plane, a helicopter, a drone, etc.), a maritime vessel (e.g., commercial shipping vessels, ships, yachts, boats or other watercraft), a submarine, a locomotive or rail-based vehicle (e.g., a train, a tram, etc.), a military vehicle, a spacecraft, and a satellite.

In describing embodiments herein, reference may be made to a particular stationary application (e.g., grid, micro-grid, data centers, cloud computing environments) or mobile application (e.g., an electric car). Such references are made for ease of explanation and do not mean that a particular embodiment is limited for use to only that particular mobile or stationary application. Embodiments of systems providing power to a motor can be used in both mobile and stationary applications. While certain configurations may be more suitable to some applications over others, all example embodiments disclosed herein are capable of use in both mobile and stationary applications unless otherwise noted.

Examples of Module-Based Energy Systems

FIG. **1**A is a block diagram depicts an example embodiment of a module-based energy system **100**. Here, system **100** includes control system **102** communicatively coupled with N converter-source modules **108-1** through **108**-N, over communication paths or links **106-1** through **106**-N, respectively. Modules **108** are configured to store energy and output the energy as needed to a load **101** (or other modules **108**). In these embodiments, any number of two or more modules **108** can be used (e.g., N is greater than or equal to two). Modules **108** can be connected to each other in a variety of manners as will be described in more detail with respect to FIGS. **7**A-**7**E. For ease of illustration, in FIGS. **1**A-**1**C, modules **108** are shown connected in series, or as a one dimensional array, where the Nth module is coupled to load **101**.

System **100** is configured to supply power to load **101**. Load **101** can be any type of load such as a motor or a grid. System **100** is also configured to store power received from a charge source. FIG. **1**F is a block diagram depicting an example embodiment of system **100** with a power input interface **151** for receiving power from a charge source **150** and a power output interface for outputting power to load **101**. In this embodiment system **100** can receive and store power over interface **151** at the same time as outputting power over interface **152**. FIG. **1**G is a block diagram depicting another example embodiment of system **100** with a switchable interface **154**. In this embodiment, system **100** can select, or be instructed to select, between receiving power from charge source **150** and outputting power to load **101**. System **100** can be configured to supply multiple loads **101**, including both primary and auxiliary loads, and/or receive power from multiple charge sources **150** (e.g., a utility-operated power grid and a local renewable energy source (e.g., solar)).

FIG. **1**B depicts another example embodiment of system **100**. Here, control system **102** is implemented as a master control device (MCD) **112** communicatively coupled with N different local control devices (LCDs) **114-1** through **114**-N over communication paths or links **115-1** through **115**-N, respectively. Each LCD **114-1** through **114**-N is communicatively coupled with one module **108-1** through **108**-N over communication paths or links **116-1** through **116**-N, respectively, such that there is a 1:1 relationship between LCDs **114** and modules **108**.

FIG. **1**C depicts another example embodiment of system **100**. Here, MCD **112** is communicatively coupled with M different LCDs **114-1** to **114**-M over communication paths or links **115-1** to **115**-M, respectively. Each LCD **114** can be coupled with and control two or more modules **108**. In the example shown here, each LCD **114** is communicatively coupled with two modules **108**, such that M LCDs **114-1** to **114**-M are coupled with **2**M modules **108-1** through **108-2**M over communication paths or links **116-1** to **116-2**M, respectively.

Control system **102** can be configured as a single device (e.g., FIG. **1**A) for the entire system **100** or can be distributed across or implemented as multiple devices (e.g., FIGS. **1**B-**1**C). In some embodiments, control system **102** can be distributed between LCDs **114** associated with the modules **108**, such that no MCD **112** is necessary and can be omitted from system **100**.

Control system **102** can be configured to execute control using software (instructions stored in memory that are executable by processing circuitry), hardware, or a combination thereof. The one or more devices of control system **102** can each include processing circuitry **120** and memory **122** as shown here. Example implementations of processing circuitry and memory are described further below.

Control system **102** can have a communicative interface for communicating with devices **104** external to system **100** over a communication link or path **105**. For example, control system **102** (e.g., MCD **112**) can output data or information about system **100** to another control device **104** (e.g., the Electronic Control Unit (ECU) or Motor Control Unit (MCU) of a vehicle in a mobile application, grid controller in a stationary application, etc.).

Communication paths or links **105**, **106**, **115**, **116**, and **118** (FIG. **2**B) can each be wired (e.g., electrical, optical) or wireless communication paths that communicate data or information bidirectionally, in parallel or series fashion. Data can be communicated in a standardized (e.g., IEEE, ANSI) or custom (e.g., proprietary) format. In automotive applications, communication paths **115** can be configured to communicate according to FlexRay or CAN protocols. Communication paths **106**, **115**, **116**, and **118** can also provide wired power to directly supply the operating power for control system **102** from one or more modules **108**. For example, the operating power for each LCD **114** can be supplied only by the one or more modules **108** to which that LCD **114** is connected and the operating power for MCD **112** can be supplied indirectly from one or more of modules **108** (e.g., such as through a car's power network).

Control system **102** is configured to control one or more modules **108** based on status information received from the same or different one or more of modules **108**. Control can also be based on one or more other factors, such as requirements of load **101**. Controllable aspects include, but are not limited to, one or more of voltage, current, phase, and/or output power of each module **108**.

Status information of every module **108** in system **100** can be communicated to control system **102**, which can independently control every module **108-1** . . . **108**-N. Other variations are possible. For example, a particular module **108** (or subset of modules **108**) can be controlled based on status information of that particular module **108** (or subset), based on status information of a different module **108** that is not that particular module **108** (or subset), based on status information of all modules **108** other than that particular module **108** (or subset) based on status information of that particular module **108** (or subset) and status information of at least one other module **108** that is not that particular module **108** (or subset), or based on status information of all modules **108** in system **100**.

The status information can be information about one or more aspects, characteristics, or parameters of each module **108**. Types of status information include, but are not limited to, the following aspects of a module **108** or one or more components thereof (e.g., energy source, energy buffer, converter, monitor circuitry): State of Charge (SOC) (e.g., the level of charge of an energy source relative to its capacity, such as a fraction or percent) of the one or more energy sources of the module, State of Health (SOH) (e.g., a figure of merit of the condition of an energy source compared to its ideal conditions) of the one or more energy sources of the module, temperature of the one or more energy sources or other components of the module, capacity of the one or more energy sources of the module, voltage of the one or more energy sources and/or other components of the module, current of the one or more energy sources and/or other components of the module, and/or the presence of absence of a fault in any one or more of the components of the module.

LCDs **114** can be configured to receive the status information from each module **108**, or determine the status information from monitored signals or data received from or within each module **108**, and communicate that information to MCD **112**. In some embodiments, each LCD **114** can communicate raw collected data to MCD **112**, which then algorithmically determines the status information on the basis of that raw data. MCD **112** can then use the status information of modules **108** to make control determinations accordingly. The determinations may take the form of instructions, commands, or other information (such as a modulation index described herein) that can be utilized by LCDs **114** to either maintain or adjust the operation of each module **108**.

For example, MCD **112** may receive status information and assess that information to determine a difference between at least one module **108** (e.g., a component thereof) and at least one or more other modules **108** (e.g., comparable components thereof). For example, MCD **112** may determine that a particular module **108** is operating with one of the following conditions as compared to one or more other modules **108**: with a relatively lower or higher SOC, with a relatively lower or higher SOH, with a relatively lower or higher capacity, with a relatively lower or higher voltage, with a relatively lower or higher current, with a relatively lower or higher temperature, or with or without a fault. In such examples, MCD **112** can output control information that causes the relevant aspect (e.g., output voltage, current, power, temperature) of that particular module **108** to be reduced or increased (depending on the condition). In this manner, the utilization of an outlier module **108** (e.g., operating with a relatively lower SOC or higher temperature), can be reduced so as to cause the relevant parameter of that module **108** (e.g., SOC or temperature) to converge towards that of one or more other modules **108**.

The determination of whether to adjust the operation of a particular module **108** can be made by comparison of the status information to predetermined thresholds, limits, or conditions, and not necessarily by comparison to statuses of other modules **108**. The predetermined thresholds, limits, or conditions can be static thresholds, limits, or conditions, such as those set by the manufacturer that do not change during use. The predetermined thresholds, limits, or conditions can be dynamic thresholds, limits, or conditions, that are permitted to change, or that do change, during use. For example, MCD **112** can adjust the operation of a module **108** if the status information for that module **108** indicates it to be operating in violation (e.g., above or below) of a predetermined threshold or limit, or outside of a predetermined range of acceptable operating conditions. Similarly, MCD **112** can adjust the operation of a module **108** if the status information for that module **108** indicates the presence of an actual or potential fault (e.g., an alarm, or warning) or indicates the absence or removal of an actual or potential fault. Examples of a fault include, but are not limited to, an actual failure of a component, a potential failure of a component, a short circuit or other excessive current condition, an open circuit, an excessive voltage condition, a failure to receive a communication, the receipt of corrupted data, and the like. Depending on the type and severity of the fault, the faulty module's utilization can be decreased to avoid damaging the module, or the module's utilization can be ceased altogether.

MCD **112** can control modules **108** within system **100** to achieve or converge towards a desired target. The target can be, for example, operation of all modules **108** at the same or similar levels with respect to each other, or within predetermined thresholds limits, or conditions. This process is also referred to as balancing or seeking to achieve balance in the operation or operating characteristics of modules **108**. The term "balance" as used herein does not require absolute equality between modules **108** or components thereof, but rather is used in a broad sense to convey that operation of system **100** can be used to actively reduce disparities in operation between modules **108** that would otherwise exist.

MCD **112** can communicate control information to LCD **114** for the purpose of controlling the modules **108** associated with the LCD **114**. The control information can be, e.g., a modulation index and a reference signal as described herein, a modulated reference signal, or otherwise. Each LCD **114** can use (e.g., receive and process) the control information to generate switch signals that control operation of one or more components (e.g., a converter) within the associated module(s) **108**. In some embodiments, MCD **112** generates the switch signals directly and outputs them to LCD **114**, which relays the switch signals to the intended module component.

All or a portion of control system **102** can be combined with a system external control device **104** that controls one or more other aspects of the mobile or stationary application. When integrated in this shared or common control device (or subsystem), control of system **100** can be implemented in any desired fashion, such as one or more software applications executed by processing circuitry of the shared device, with hardware of the shared device, or a combination thereof. Non-exhaustive examples of external control devices **104** include: a vehicular ECU or MCU having control capability for one or more other vehicular functions (e.g., motor control, driver interface control, traction control, etc.); a grid or micro-grid controller having responsibility for one or more other power management functions (e.g., load interfacing, load power requirement forecasting, transmission and switching, interface with charge sources (e.g., diesel, solar, wind), charge source power forecasting, back up source monitoring, asset dispatch, etc.); and a data center control subsystem (e.g., environmental control, network control, backup control, etc.).

FIGS. **1**D and **1**E are block diagrams depicting example embodiments of a shared or common control device (or system) **132** in which control system **102** can be implemented. In FIG. **1**D, common control device **132** includes master control device **112** and external control device **104**. Master control device **112** includes an interface **141** for communication with LCDs **114** over path **115**, as well as an interface **142** for communication with external control device **104** over internal communication bus **136**. External control device **104** includes an interface **143** for communication with master control device **112** over bus **136**, and an interface **144** for communication with other entities (e.g., components of the vehicle or grid) of the overall application over communication path **136**. In some embodiments, common control device **132** can be integrated as a common housing or package with devices **112** and **104** implemented as discrete integrated circuit (IC) chips or packages contained therein.

In FIG. **1**E, external control device **104** acts as common control device **132**, with the master control functionality implemented as a component **112** within device **104**. This component **112** can be or include software or other program instructions stored and/or hardcoded within memory of device **104** and executed by processing circuitry thereof. The component can also contain dedicated hardware. The component can be a self-contained module or core, with one or more internal hardware and/or software interfaces (e.g., application program interface (API)) for communication with the operating software of external control device **104**. External control device **104** can manage communication with LCDs **114** over interface **141** and other devices over interface **144**. In various embodiments, device **104**/**132** can be integrated as a single IC chip, can be integrated into multiple IC chips in a single package, or integrated as multiple semiconductor packages within a common housing.

In the embodiments of FIGS. **1**D and **1**E, the master control functionality of system **102** is shared in common device **132**, however, other divisions of shared control or permitted. For example, part of the master control functionality can be distributed between common device **132** and a dedicated MCD **112**. In another example, both the master control functionality and at least part of the local control functionality can be implemented in common device **132** (e.g., with remaining local control functionality implemented in LCDs **114**). In some embodiments, all of control system **102** is implemented in common device (or subsystem) **132**. In some embodiments, local control functionality is implemented within a device shared with another component of each module **108**, such as a Battery Management System (BMS).

Examples of Modules within Cascaded Energy Systems

Module **108** can include one or more energy sources and a power electronics converter and, if desired, an energy buffer. FIGS. **2**A-**2**B are block diagrams depicting additional example embodiments of system **100** with module **108** having a power converter **202**, an energy buffer **204**, and an energy source **206**. Converter **202** can be a voltage converter or a current converter. The embodiments are described herein with reference to voltage converters, although the embodiments are not limited to such. Converter **202** can be configured to convert a direct current (DC) signal from energy source **204** into an alternating current (AC) signal and output it over power connection **110** (e.g., an inverter). Converter **202** can also receive an AC or DC signal over connection **110** and apply it to energy source **204** with either polarity in a continuous or pulsed form. Converter **202** can be or include an arrangement of switches (e.g., power transistors) such as a half bridge of full bridge (H-bridge). In some embodiments converter **202** includes only switches and the converter (and the module as a whole) does not include a transformer.

Converter **202** can be also (or alternatively) be configured to perform AC to DC conversion (e.g., a rectifier) such as to charge a DC energy source from an AC source, DC to DC conversion, and/or AC to AC conversion (e.g., in combination with an AC-DC converter). In some embodiments, such as to perform AC-AC conversion, converter **202** can include a transformer, either alone or in combination with one or more power semiconductors (e.g., switches, diodes, thyristors, and the like). In other embodiments, such as those where weight and cost is a significant factor, converter **202** can be configured to perform the conversions with only power switches, power diodes, or other semiconductor devices and without a transformer.

Energy source **206** is preferably a robust energy storage device capable of outputting direct current and having an energy density suitable for energy storage applications for electrically powered devices. The fuel cell can be a single fuel cell, multiple fuel cells connected in series or parallel, or a fuel cell module. Two or more energy sources can be included in each module, and the two or more sources can include two batteries of the same or different type, two capacitors of the same or different type, two fuel cells of the same or different type, one or more batteries combined with one or more capacitors and/or fuel cells, and one or more capacitors combined with one or more fuel cells.

Energy source **206** can be an electrochemical battery, such as a single battery cell or multiple battery cells connected together in a battery module or array, or any combination thereof. FIGS. **4**A-**4**D are schematic diagrams depicting example embodiments of energy source **206** configured as a single battery cell **402** (FIG. **4**A), a battery module with a series connection of multiple (e.g., four) cells **402** (FIG. **4**B), a battery module with a parallel connection of single cells **402** (FIG. **4**C), and a battery module with a parallel connection with legs having multiple (e.g., two) cells **402** each (FIG. **4**D). Examples of batteries types include solid state batteries, liquid electrotype based batteries, liquid phase batteries as well as flow batteries such as lithium (Li) metal batteries, Li ion batteries, Li air batteries, sodium ion batteries, potassium ion batteries, magnesium ion batteries, alkaline batteries, nickel metal hydride batteries, nickel sulfate batteries, lead acid batteries, zinc-air batteries, and others. Some examples of Li ion battery types include Li cobalt oxide (LCO), Li manganese oxide (LMO), Li nickel manganese cobalt oxide (NMC), Li iron phosphate (LFP), Lithium nickel cobalt aluminum oxide (NCA), and Li titanate (LTO).

Energy source **206** can also be a high energy density (HED) capacitor, such as an ultracapacitor or supercapacitor. An HED capacitor can be configured as a double layer capacitor (electrostatic charge storage), pseudocapacitor (electrochemical charge storage), hybrid capacitor (electrostatic and electrochemical), or otherwise, as opposed to a solid dielectric type of a typical electrolytic capacitor. The HED capacitor can have an energy density of 10 to 100 times (or higher) that of an electrolytic capacitor, in addition to a higher capacity. For example, HED capacitors can have a specific energy greater than 1.0 watt hours per kilogram (Wh/kg), and a capacitance greater than 10-100 farads (F). As with the batteries described with respect to FIGS. **4**A-**4**D, energy source **206** can be configured as a single HED capacitor or multiple HED capacitors connected together in an array (e.g., series, parallel, or a combination thereof).

Energy source **206** can also be a fuel cell. Examples of fuel cells include proton-exchange membrane fuel cells (PEMFC), phosphoric acid fuel cells (PAFC), solid acid fuel cells, alkaline fuel cells, high temperature fuel cells, solid oxide fuel cells, molten electrolyte fuel cells, and others. As with the batteries described with respect to FIGS. **4**A-**4**D, energy source **206** can be configured as a single fuel cell or multiple fuel cells connected together in an array (e.g., series, parallel, or a combination thereof). The aforementioned examples of batteries, capacitors, and fuel cells are not intended to form an exhaustive list, and those of ordinary skill in the art will recognize other variants that fall within the scope of the present subject matter.

Energy buffer **204** can dampen or filter fluctuations in current across the DC line or link (e.g., $+V_{DCL}$ and $-V_{DCL}$ as described below), to assist in maintaining stability in the DC link voltage. These fluctuations can be relatively low (e.g., kilohertz) or high (e.g., megahertz) frequency fluctuations or harmonics caused by the switching of converter **202**, or other transients. These fluctuations can be absorbed by buffer **204** instead of being passed to source **206** or to ports IO3 and IO4 of converter **202**.

Power connection **110** is a connection for transferring energy or power to, from and through module **108**. Module **108** can output energy from energy source **206** to power connection **110**, where it can be transferred to other modules of the system or to a load. Module **108** can also receive energy from other modules **108** or a charging source (DC charger, single phase charger, multi-phase charger). Signals can also be passed through module **108** bypassing energy source **206**. The routing of energy or power into and out of module **108** is performed by converter **202** under the control of LCD **114** (or another entity of system **102**).

In the embodiment of FIG. **2**A, LCD **114** is implemented as a component separate from module **108** (e.g., not within a shared module housing) and is connected to and capable of communication with converter **202** via communication path **116**. In the embodiment of FIG. **2**B, LCD **114** is included as a component of module **108** and is connected to and capable of communication with converter **202** via internal communication path **118** (e.g., a shared bus or discrete connections). LCD **114** can also be capable of receiving signals from, and transmitting signals to, energy buffer **204** and/or energy source **206** over paths **116** or **118**.

Module **108** can also include monitor circuitry **208** configured to monitor (e.g., collect, sense, measure, and/or determine) one or more aspects of module **108** and/or the components thereof, such as voltage, current, temperature or other operating parameters that constitute status information (or can be used to determine status information by, e.g., LCD **114**). A main function of the status information is to describe the state of the one or more energy sources **206** of the module **108** to enable determinations as to how much to utilize the energy source in comparison to other sources in system **100**, although status information describing the state of other components (e.g., voltage, temperature, and/or presence of a fault in buffer **204**, temperature and/or presence of a fault in converter **202**, presence of a fault elsewhere in module **108**, etc.) can be used in the utilization determination as well. Monitor circuitry **208** can include one or more sensors, shunts, dividers, fault detectors, Coulomb counters, controllers or other hardware and/or software configured to monitor such aspects. Monitor circuitry **208** can be separate from the various components **202**, **204**, and **206**, or can be integrated with each component **202**, **204**, and **206** (as shown in FIGS. **2**A-**2**B), or any combination thereof. In some embodiments, monitor circuitry **208** can be part of or shared with a Battery Management System (BMS) for a battery energy source **204**. Discrete circuitry is not needed to monitor each type of status information, as more than one type of status information can be monitored with a single circuit or device, or otherwise algorithmically determined without the need for additional circuits.

LCD **114** can receive status information (or raw data) about the module components over communication paths **116**, **118**. LCD **114** can also transmit information to module components over paths **116**, **118**. Paths **116** and **118** can include diagnostics, measurement, protection, and control signal lines. The transmitted information can be control signals for one or more module components. The control signals can be switch signals for converter **202** and/or one or more signals that request the status information from module components. For example, LCD **114** can cause the status information to be transmitted over paths **116**, **118** by requesting the status information directly, or by applying a stimulus (e.g., voltage) to cause the status information to be generated, in some cases in combination with switch signals that place converter **202** in a particular state.

The physical configuration or layout of module **108** can take various forms. In some embodiments, module **108** can include a common housing in which all module components, e.g., converter **202**, buffer **204**, and source **206**, are housed, along with other optional components such as an integrated LCD **114**. In other embodiments, the various components can be separated in discrete housings that are secured together. FIG. **2**C is a block diagram depicting an example embodiment of a module **108** having a first housing **220** that holds an energy source **206** of the module and accompanying electronics such as monitor circuitry **208** (not shown), a second housing **222** that holds module electronics such as converter **202**, energy buffer **204**, and other accompany electronics such as monitor circuitry (not shown), and a third housing **224** that holds LCD **114** (not shown) for the module **108**. Electrical connections between the various module components can proceed through the housings **220**, **222**, **224** and can be exposed on any of the housing exteriors for connection with other devices such as other modules **108** or MCD **112**.

Modules **108** of system **100** can be physically arranged with respect to each other in various configurations that depend on the needs of the application and the number of loads. For example, in a stationary application where system **100** provides power for a microgrid, modules **108** can be placed in one or more racks or other frameworks. Such configurations may be suitable for larger mobile applications as well, such as maritime vessels. Alternatively, modules **108** can be secured together and located within a common housing, referred to as a pack. A rack or a pack may have its own dedicated cooling system shared across all modules. Pack configurations are useful for smaller mobile applications such as electric cars. System **100** can be implemented with one or more racks (e.g., for parallel supply to a microgrid) or one or more packs (e.g., serving different motors of the vehicle), or combination thereof. FIG. **2**D is a block diagram depicting an example embodiment of system **100** configured as a pack with nine modules **108** electrically and physically coupled together within a common housing **230**.

Examples of these and further configurations are described in Int'l. Publ. No. 2020/205574, which is incorporated by reference herein in its entirety for all purposes.

FIGS. **3**A-**3**C are block diagrams depicting example embodiments of modules **108** having various electrical configurations. These embodiments are described as having one LCD **114** per module **108**, with the LCD **114** housed within the associated module, but can be configured otherwise as described herein. FIG. **3**A depicts a first example configuration of a module **108**A within system **100**. Module **108**A includes energy source **206**, energy buffer **204**, and converter **202**A. Each component has power connection ports (e.g., terminals, connectors) into which power can be input and/or from which power can be output, referred to herein as IO ports. Such ports can also be referred to as input ports or output ports depending on the context.

Energy source **206** can be configured as any of the energy source types described herein (e.g., a battery as described with respect to FIGS. **4**A-**4**D, an HED capacitor, a fuel cell, or otherwise). Ports IO**1** and IO**2** of energy source **206** can be connected to ports IO**1** and IO**2**, respectively, of energy buffer **204**. Energy buffer **204** can be configured to buffer or filter high and low frequency energy pulsations arriving at buffer **204** through converter **202**, which can otherwise degrade the performance of module **108**. The topology and components for buffer **204** are selected to accommodate the maximum permissible amplitude of these high frequency voltage pulsations. Several (non-exhaustive) example embodiments of energy buffer **204** are depicted in the schematic diagrams of FIGS. **5**A-**5**C. In FIG. **5**A, buffer **204** is an electrolytic and/or film capacitor C_{EB}, in FIG. **5**B buffer **204** is a Z-source network **710**, formed by two inductors L_{EB1} and L_{EB2} and two electrolytic and/or film capacitors C_{EB1} and C_{EB2}, and in FIG. **5**C buffer **204** is a quasi Z-source network **720**, formed by two inductors L_{EB1} and L_{EB2}, two electrolytic and/or film capacitors C_{EB1} and C_{EB2} and a diode D_{EB}.

Ports IO**3** and IO**4** of energy buffer **204** can be connected to ports IO**1** and IO**2**, respectively, of converter **202**A, which can be configured as any of the power converter types described herein. FIG. **6**A is a schematic diagram depicting an example embodiment of converter **202**A configured as a DC-AC converter that can receive a DC voltage at ports IO**1** and IO**2** and switch to generate pulses at ports IO**3** and IO**4**. Converter **202**A can include multiple switches, and here converter **202**A includes four switches S**3**, S**4**, S**5**, S**6** arranged in a full bridge configuration. Control system **102** or LCD **114** can independently control each switch via control input lines **118-3** to each gate.

The switches can be any suitable switch type, such as power semiconductors like the metal-oxide-semiconductor field-effect transistors (MOSFETs) shown here, insulated gate bipolar transistors (IGBTs), or gallium nitride (GaN) transistors. Semiconductor switches can operate at relatively high switching frequencies, thereby permitting converter **202** to be operated in pulse-width modulated (PWM) mode if desired, and to respond to control commands within a relatively short interval of time. This can provide a high tolerance of output voltage regulation and fast dynamic behavior in transient modes.

In this embodiment, a DC line voltage V_{DCL} can be applied to converter **202** between ports IO**1** and IO**2**. By connecting V_{DCL} to ports IO**3** and IO**4** by different combinations of switches S**3**, S**4**, S**5**, S**6**, converter **202** can generate three different voltage outputs at ports IO**3** and IO**4**: $+V_{DCL}$, 0, and $-V_{DCL}$. A switch signal provided to each switch controls whether the switch is on (closed) or off (open). To obtain $+V_{DCL}$, switches S**3** and S**6** are turned on while S**4** and S**5** are turned off, whereas $-V_{DCL}$ can be obtained by turning on switches S**4** and S**5** and turning off S**3** and S**6**. The output voltage can be set to zero (including near zero) or a reference voltage by turning on S**3** and S**5** with S**4** and S**6** off, or by turning on S**4** and S**6** with S**3** and S**5** off. These voltages can be output from module **108** over power connection **110**. Ports IO**3** and IO**4** of converter **202** can be connected to (or form) module IO ports **1** and **2** of power connection **110**, so as to generate the output voltage for use with output voltages from other modules **108**.

The control or switch signals for the embodiments of converter **202** described herein can be generated in different ways depending on the control technique utilized by system **100** to generate the output voltage of converter **202**. In some embodiments, the control technique is a PWM technique such as space vector pulse-width modulation (SVPWM) or sinusoidal pulse-width modulation (SPWM), or variations thereof. FIG. **8**A is a graph of voltage versus time depicting an example of an output voltage waveform **802** of converter **202**. For ease of description, the embodiments herein will be described in the context of a PWM control technique, although the embodiments are not limited to such. Other classes of techniques can be used. One alternative class is based on hysteresis, examples of which are described in Int'l Publ. Nos. WO 2018/231810A1, WO 2018/232403A1, and WO 2019/183553A1, which are incorporated by reference herein for all purposes.

Each module **108** can be configured with multiple energy sources **206** (e.g., two, three, four, or more). Each energy source **206** of module **108** can be controllable (switchable) to supply power to connection **110** (or receive power from a charge source) independent of the other sources **206** of the module. For example, all sources **206** can output power to connection **110** (or be charged) at the same time, or only one (or a subset) of sources **206** can supply power (or be charged) at any one time. In some embodiments, the sources **206** of the module can exchange energy between them, e.g., one source **206** can charge another source **206**. Each of the sources **206** can be configured as any energy source described herein (e.g., battery, HED capacitor, fuel cell). Each of the sources **206** can be the same type (e.g., each can be a battery), or a different type (e.g., a first source can be a battery and a second source can be an HED capacitor, or a first source can be a battery having a first type (e.g., NMC) and a second source can be a battery having a second type (e.g., LFP).

FIG. **3**B is a block diagram depicting an example embodiment of a module **108**B in a dual energy source configuration with a primary energy source **206**A and secondary energy source **206**B. Ports IO**1** and IO**2** of primary source **202**A can be connected to ports IO**1** and IO**2** of energy buffer **204**. Module **108**B includes a converter **202**B having an additional IO port. Ports IO**3** and IO**4** of buffer **204** can be connected ports IO**1** and IO**2**, respectively, of converter **202**B. Ports IO**1** and IO**2** of secondary source **206**B can be connected to ports IO**5** and IO**2**, respectively, of converter **202**B (also connected to port IO**4** of buffer **204**).

In this example embodiment of module **108**B, primary energy source **202**A, along with the other modules **108** of system **100**, supplies the average power needed by the load. Secondary source **202**B can serve the function of assisting energy source **202** by providing additional power at load power peaks, or absorbing excess power, or otherwise.

As mentioned both primary source **206**A and secondary source **206**B can be utilized simultaneously or at separate times depending on the switch state of converter **202**B. If at the same time, an electrolytic and/or a film capacitor (CEs) can be placed in parallel with source **206**B as depicted in FIG. **4**E to act as an energy buffer for the source **206**B, or energy source **206**B can be configured to utilize an HED capacitor in parallel with another energy source (e.g., a battery or fuel cell) as depicted in FIG. **4**F.

FIGS. **6**B and **6**C are schematic views depicting example embodiments of converters **202**B and **202**C, respectively. Converter **202**B includes switch circuitry portions **601** and **602**A. Portion **601** includes switches S**3** through S**6** configured as a full bridge in similar manner to converter **202**A, and is configured to selectively couple IO**1** and IO**2** to either of IO**3** and IO**4**, thereby changing the output voltages of module **108**B. Portion **602**A includes switches S**1** and S**2** configured as a half bridge and coupled between ports IO**1** and IO**2**. A coupling inductor L_C is connected between port IO**5** and a node**1** present between switches S**1** and S**2** such that switch portion **602**A is a bidirectional converter that can regulate (boost or buck) voltage (or inversely current). Switch portion **602**A can generate two different voltages at node**1**, which are $+V_{DCL2}$ and 0, referenced to port IO**2**, which can be at virtual zero potential. The current drawn from or input to energy source **202**B can be controlled by regulating the voltage on coupling inductor L_C, using, for example, a pulse-width modulation technique or a hysteresis control method for commutating switches S**1** and S**2**. Other techniques can also be used.

Converter **202**C differs from that of **202**B as switch portion **602**B includes switches S**1** and S**2** configured as a half bridge and coupled between ports IO**5** and IO**2**. A coupling inductor L_C is connected between port IO**1** and a node**1** present between switches S**1** and S**2** such that switch portion **602**B is configured to regulate voltage.

Control system **102** or LCD **114** can independently control each switch of converters **202**B and **202**C via control input lines **118-3** to each gate. In these embodiments and that of FIG. **6**A, LCD **114** (not MCD **112**) generates the switching signals for the converter switches. Alternatively, MCD **112** can generate the switching signals, which can be communicated directly to the switches, or relayed by LCD **114**.

In embodiments where a module **108** includes three or more energy sources **206**, converters **202**B and **202**C can be scaled accordingly such that each additional energy source **206**B is coupled to an additional IO port leading to an additional switch circuitry portion **602**A or **602**B, depending on the needs of the particular source. For example a dual source converter **202** can include both switch portions **202**A and **202**B.

Modules **108** with multiple energy sources **206** are capable of performing additional functions such as energy sharing between sources **206**, energy capture from within the application (e.g., regenerative braking), charging of the primary source by the secondary source even while the overall system is in a state of discharge, and active filtering of the module output. Examples of these functions are described in more detail in Int'l. Publ. No. WO 2020/205574, filed Mar. 27, 2020, and titled Module-Based Energy Systems Capable Of Cascaded And Interconnected Configurations, And Methods Related Thereto, and Int'l. Publ. No. WO 2019/183553, filed Mar. 22, 2019, and titled Systems and Methods for Power Management and Control, both of which are incorporated by reference herein in their entireties for all purposes.

Each module **108** can be configured to supply one or more auxiliary loads with its one or more energy sources **206**. Auxiliary loads are loads that require lower voltages than the primary load **101**. Examples of auxiliary loads can be, for example, an on-board electrical network of an electric vehicle, or an HVAC system of an electric vehicle. The load of system **100** can be, for example, one of the phases of the electric vehicle motor or electrical grid. This embodiment can allow a complete decoupling between the electrical characteristics (terminal voltage and current) of the energy source and those of the loads.

FIG. **3**C is a block diagram depicting an example embodiment of a module **108**C configured to supply power to a first auxiliary load **301** and a second auxiliary load **302**, where module **108**C includes an energy source **206**, energy buffer **204**, and converter **202**B coupled together in a manner similar to that of FIG. **3**B. First auxiliary load **301** requires a voltage equivalent to that supplied from source **206**. Load **301** is coupled to IO ports **3** and **4** of module **108**C, which are in turn coupled to ports IO**1** and IO**2** of source **206**. Source **206** can output power to both power connection **110** and load **301**. Second auxiliary load **302** requires a constant voltage lower than that of source **206**. Load **302** is coupled to IO ports **5** and **6** of module **108**C, which are coupled to ports IO**5** and IO**2**, respectively, of converter **202**B. Converter **202**B can include switch portion **602** having coupling inductor L_C coupled to port IO**5** (FIG. **6**B). Energy supplied by source **206** can be supplied to load **302** through switch portion **602** of converter **202**B. It is assumed that load **302** has an input capacitor (a capacitor can be added to module **108**C if not), so switches S**1** and S**2** can be commutated to regulate the voltage on and current through coupling inductor L_C and thus produce a stable constant voltage for load **302**. This regulation can step down the voltage of source **206** to the lower magnitude voltage is required by load **302**.

Module **108**C can thus be configured to supply one or more first auxiliary loads in the manner described with respect to load **301**, with the one or more first loads coupled to IO ports **3** and **4**. Module **108**C can also be configured to supply one or more second auxiliary loads in the manner described with respect to load **302**. If multiple second auxiliary loads **302** are present, then for each additional load **302** module **108**C can be scaled with additional dedicated module output ports (like **5** and **6**), an additional dedicated switch portion **602**, and an additional converter IO port coupled to the additional portion **602**.

Energy source **206** can thus supply power for any number of auxiliary loads (e.g., **301** and **302**), as well as the corresponding portion of system output power needed by primary load **101**. Power flow from source **206** to the various loads can be adjusted as desired.

Module **108** can be configured as needed with two or more energy sources **206** (FIG. **3**B) and to supply first and/or second auxiliary loads (FIG. **3**C) through the addition of a switch portion **602** and converter port IO**5** for each additional source **206**B or second auxiliary load **302**. Additional module IO ports (e.g., **3**, **4**, **5**, **6**) can be added as needed. Module **108** can also be configured as an interconnection module to exchange energy (e.g., for balancing) between two or more arrays, two or more packs, or two or more systems **100** as described further herein. This interconnection functionality can likewise be combined with multiple source and/or multiple auxiliary load supply capabilities.

Control system **102** can perform various functions with respect to the components of modules **108**A, **108**B, and **108**C. These functions can include management of the utilization (amount of use) of each energy source **206**, protection of energy buffer **204** from over-current, over-voltage and high temperature conditions, and control and protection of converter **202**.

For example, to manage (e.g., adjust by increasing, decreasing, or maintaining) utilization of each energy source **206**, LCD **114** can receive one or more monitored voltages, temperatures, and currents from each energy source **206** (or monitor circuitry). The monitored voltages can be at least one of, preferably all, voltages of each elementary component independent of the other components (e.g., each individual battery cell, HED capacitor, and/or fuel cell) of the source **206**, or the voltages of groups of elementary components as a whole (e.g., voltage of the battery array, HED capacitor array, and/or fuel cell array). Similarly the monitored temperatures and currents can be at least one of, preferably all, temperatures and currents of each elementary component independent of the other components of the source **206**, or the temperatures and currents of groups of elementary components as a whole, or any combination thereof. The monitored signals can be status information, with which LCD **114** can perform one or more of the following: calculation or determination of a real capacity, actual State of Charge (SOC) and/or State of Health (SOH) of the elementary components or groups of elementary components; set or output a warning or alarm indication based on monitored and/or calculated status information; and/or transmission of the status information to MCD **112**. LCD **114** can receive control information (e.g., a modulation index, synchronization signal) from MCD **112** and use this control information to generate switch signals for converter **202** that manage the utilization of the source **206**.

To protect energy buffer **204**, LCD **114** can receive one or more monitored voltages, temperatures, and currents from energy buffer **204** (or monitor circuitry). The monitored voltages can be at least one of, preferably all, voltages of each elementary component of buffer **204** (e.g., of C_{EB}, C_{EB1}, C_{EB2}, L_{EB1}, L_{EB2}, D_{EB}) independent of the other components, or the voltages of groups of elementary components or buffer **204** as a whole (e.g., between IO**1** and IO**2** or between IO**3** and IO**4**). Similarly the monitored temperatures and currents can be at least one of, preferably all, temperatures and currents of each elementary component of buffer **204** independent of the other components, or the temperatures and currents of groups of elementary components or of buffer **204** as a whole, or any combination thereof. The monitored signals can be status information, with which LCD **114** can perform one or more of the following: set or output a warning or alarm indication; communicate the status information to MCD **112**; or control converter **202** to adjust (increase or decrease) the utilization of source **206** and module **108** as a whole for buffer protection.

To control and protect converter **202**, LCD **114** can receive the control information from MCD **112** (e.g., a modulated reference signal, or a reference signal and a modulation index), which can be used with a PWM technique in LCD **114** to generate the control signals for each switch (e.g., S**1** through S**6**). LCD **114** can receive a current feedback signal from a current sensor of converter **202**, which can be used for overcurrent protection together with one or more fault status signals from driver circuits (not shown) of the converter switches, which can carry information about fault statuses (e.g., short circuit or open circuit failure modes) of all switches of converter **202**. Based on this data, LCD **114** can make a decision on which combination of switching signals to be applied to manage utilization of module **108**, and potentially bypass or disconnect converter **202** (and the entire module **108**) from system **100**.

If controlling a module **108**C that supplies a second auxiliary load **302**, LCD **114** can receive one or more monitored voltages (e.g., the voltage between IO ports **5** and **6**) and one or more monitored currents (e.g., the current in coupling inductor L_C, which is a current of load **302**) in module **108**C. Based on these signals, LCD **114** can adjust the switching cycles (e.g., by adjustment of modulation index or reference waveform) of S**1** and S**2** to control (and stabilize) the voltage for load **302**.

Examples of Cascaded Energy System Topologies

Two or more modules **108** can be coupled together in a cascaded array that outputs a voltage signal formed by a superposition of the discrete voltages generated by each module **108** within the array. FIG. **7**A is a block diagram depicting an example embodiment of a topology for system **100** where N modules **108-1**, **108-2** . . . **108**-N are coupled together in series to form a serial array **700**. In this and all embodiments described herein, N can be any integer greater than one. Array **700** includes a first system IO port SIO**1** and a second system IO port SIO**2** across which is generated an array output voltage. Array **700** can be used as a DC or single phase AC energy source for DC or AC single-phase loads, which can be connected to SIO**1** and SIO**2** of array **700**. FIG. **8**A is a plot of voltage versus time depicting an example output signal produced by a single module **108** having a 48 volt energy source. FIG. **8**B is a plot of voltage versus time depicting an example single phase AC output signal generated by array **700** having six 48V modules **108** coupled in series.

System **100** can be arranged in a broad variety of different topologies to meet varying needs of the applications. System **100** can provide multi-phase power (e.g., two-phase, three-phase, four-phase, five-phase, six-phase, etc.) to a load by use of multiple arrays **700**, where each array can generate an AC output signal having a different phase angle.

FIG. **7**B is a block diagram depicting system **100** with two arrays **700**-PA and **700**-PB coupled together. Each array **700** is one-dimensional, formed by a series connection of N modules **108**. The two arrays **700**-PA and **700**-PB can each generate a single-phase AC signal, where the two AC signals have different phase angles PA and PB (e.g., 180 degrees apart). IO port **1** of module **108-1** of each array **700**-PA and **700**-PB can form or be connected to system IO ports SIO**1** and SIO**2**, respectively, which in turn can serve as a first output of each array that can provide two phase power to a load (not shown). Or alternatively ports SIO**1** and SIO**2** can be connected to provide single phase power from two parallel arrays. IO port **2** of module **108**-N of each array **700**-PA and **700**-PB can serve as a second output for each array **700**-PA and **700**-PB on the opposite end of the array from system IO ports SIO**1** and SIO**2**, and can be coupled together at a common node and optionally used for an additional system IO port SIO**3** if desired, which can serve as a neutral. This common node can be referred to as a rail, and IO port **2** of modules **108**-N of each array **700** can be referred to as being on the rail side of the arrays.

FIG. **7**C is a block diagram depicting system **100** with three arrays **700**-PA, **700**-PB, and **700**-PC coupled together. Each array **700** is one-dimensional, formed by a series connection of N modules **108**. The three arrays **700-1** and

700-2 can each generate a single-phase AC signal, where the three AC signals have different phase angles PA, PB, PC (e.g., 120 degrees apart). IO port **1** of module **108-1** of each array **700**-PA, **700**-PB, and **700**-PC can form or be connected to system IO ports SIO**1**, SIO**2**, and SIO**3**, respectively, which in turn can provide three phase power to a load (not shown). IO port **2** of module **108**-N of each array **700**-PA, **700**-PB, and **700**-PC can be coupled together at a common node and optionally used for an additional system IO port SIO**4** if desired, which can serve as a neutral.

The concepts described with respect to the two-phase and three-phase embodiments of FIGS. **7**B and **7**C can be extended to systems **100** generating still more phases of power. For example, a non-exhaustive list of additional examples includes: system **100** having four arrays **700**, each of which is configured to generate a single phase AC signal having a different phase angle (e.g., 90 degrees apart): system **100** having five arrays **700**, each of which is configured to generate a single phase AC signal having a different phase angle (e.g., 72 degrees apart); and system **100** having six arrays **700**, each array configured to generate a single phase AC signal having a different phase angle (e.g., 60 degrees apart).

System **100** can be configured such that arrays **700** are interconnected at electrical nodes between modules **108** within each array. FIG. **7**D is a block diagram depicting system **100** with three arrays **700**-PA, **700**-PB, and **700**-PC coupled together in a combined series and delta arrangement. Each array **700** includes a first series connection of M modules **108**, where M is two or greater, coupled with a second series connection of N modules **108**, where N is two or greater. The delta configuration is formed by the interconnections between arrays, which can be placed in any desired location. In this embodiment, IO port **2** of module **108**-(M+N) of array **700**-PC is coupled with IO port **2** of module **108**-M and IO port **1** of module **108**-(M+1) of array **700**-PA, IO port **2** of module **108**-(M+N) of array **700**-PB is coupled with IO port **2** of module **108**-M and IO port **1** of module **108**-(M+1) of array **700**-PC, and IO port **2** of module **108**-(M+N) of array **700**-PA is coupled with IO port **2** of module **108**-M and IO port **1** of module **108**-(M+1) of array **700**-PB.

FIG. **7**E is a block diagram depicting system **100** with three arrays **700**-PA, **700**-PB, and **700**-PC coupled together in a combined series and delta arrangement. This embodiment is similar to that of FIG. **7**D except with different cross connections. In this embodiment, IO port **2** of module **108**-M of array **700**-PC is coupled with IO port **1** of module **108-1** of array **700**-PA, IO port **2** of module **108**-M of array **700**-PB is coupled with IO port **1** of module **108-1** of array **700**-PC, and IO port **2** of module **108**-M of array **700**-PA is coupled with IO port **1** of module **108-1** of array **700**-PB. The arrangements of FIGS. **7**D and **7**E can be implemented with as little as two modules in each array **700**. Combined delta and series configurations enable an effective exchange of energy between all modules **108** of the system (interphase balancing) and phases of power grid or load, and also allows reducing the total number of modules **108** in an array **700** to obtain the desired output voltages.

In the embodiments described herein, although it is advantageous for the number of modules **108** to be the same in each array **700** within system **100**, such is not required and different arrays **700** can have differing numbers of modules **108**. Further, each array **700** can have modules **108** that are all of the same configuration (e.g., all modules are **108**A, all modules are **108**B, all modules are **108**C, or others) or different configurations (e.g., one or more modules are **108**A, one or more are **108**B, and one or more are **108**C, or otherwise). As such, the scope of topologies of system **100** covered herein is broad.

Example Embodiments of Control Methodologies

As mentioned, control of system **100** can be performed according to various methodologies, such as hysteresis or PWM. Several examples of PWM include space vector modulation and sine pulse width modulation, where the switching signals for converter **202** are generated with a phase shifted carrier technique that continuously rotates utilization of each module **108** to equally distribute power among them.

FIGS. **8**C-**8**F are plots depicting an example embodiment of a phase-shifted PWM control methodology that can generate a multilevel output PWM waveform using incrementally shifted two-level waveforms. An X-level PWM waveform can be created by the summation of (X−1)/2 two-level PWM waveforms. These two-level waveforms can be generated by comparing a reference waveform Vref to carriers incrementally shifted by 360°/(X−1). The carriers are triangular, but the embodiments are not limited to such. A nine-level example is shown in FIG. **8**C (using four modules **108**). The carriers are incrementally shifted by 360°/(9−1)=45° and compared to Vref. The resulting two-level PWM waveforms are shown in FIG. **8**E. These two-level waveforms may be used as the switching signals for semiconductor switches (e.g., S**1** though S**6**) of converters **202**. As an example with reference to FIG. **8**E, for a one-dimensional array **700** including four modules **108** each with a converter **202**, the 0° signal is for control of S**3** and the 180° signal for S**6** of the first module **108-1**, the 45° signal is for S**3** and the 225° signal for S**6** of the second module **108-2**, the 90 signal is for S**3** and the 270 signal is for S**6** of the third module **108-3**, and the 135 signal is for S**3** and the 315 signal is for S**6** of the fourth module **108-4**. The signal for S**3** is complementary to S**4** and the signal for S**5** is complementary to S**6** with sufficient dead-time to avoid shoot through of each half-bridge. FIG. **8**F depicts an example single phase AC waveform produced by superposition (summation) of output voltages from the four modules **108**.

An alternative is to utilize both a positive and a negative reference signal with the first (N−1)/2 carriers. A nine-level example is shown in FIG. **8**D. In this example, the 0° to 135° switching signals (FIG. **8**E) are generated by comparing +Vref to the 0° to 135° carriers of FIG. **8**D and the 180° to 315° switching signals are generated by comparing −Vref to the 0° to 135° carriers of FIG. **8**D. However, the logic of the comparison in the latter case is reversed. Other techniques such as a state machine decoder may also be used to generate gate signals for the switches of converter **202**.

In multi-phase system embodiments, the same carriers can be used for each phase, or the set of carriers can be shifted as a whole for each phase. For example, in a three phase system with a single reference voltage (Vref), each array **700** can use the same number of carriers with the same relative offsets as shown in FIGS. **8**C and **8**D, but the carriers of the second phase are shift by 120 degrees as compared to the carriers of the first phase, and the carriers of the third phase are shifted by 240 degrees as compared to the carriers of the first phase. If a different reference voltage is available for each phase, then the phase information can be carried in the reference voltage and the same carriers can be used for each phase. In many cases the carrier frequencies will be fixed, but in some example embodiments, the carrier frequencies can be adjusted, which can help to reduce losses in EV motors under high current conditions.

The appropriate switching signals can be provided to each module by control system **102**. For example, MCD **112** can provide Vref and the appropriate carrier signals to each LCD **114** depending upon the module or modules **108** that LCD **114** controls, and the LCD **114** can then generate the switching signals. Or all LCDs **114** in an array can be provided with all carrier signals and the LCD can select the appropriate carrier signals.

The relative utilizations of each module **108** can adjusted based on status information to perform balancing or of one or more parameters as described herein. Balancing of parameters can involve adjusting utilization to minimize parameter divergence over time as compared to a system where individual module utilization adjustment is not performed. The utilization can be the relative amount of time a module **108** is discharging when system **100** is in a discharge state, or the relative amount of time a module **108** is charging when system **100** is in a charge state.

As described herein, modules **108** can be balanced with respect to other modules in an array **700**, which can be referred to as intra-array or intraphase balancing, and different arrays **700** can be balanced with respect to each other, which can be referred to as interarray or interphase balancing. Arrays **700** of different subsystems can also be balanced with respect to each other. Control system **102** can simultaneously perform any combination of intraphase balancing, interphase balancing, utilization of multiple energy sources within a module, active filtering, and auxiliary load supply.

FIG. **9**A is a block diagram depicting an example embodiment of an array controller **900** of control system **102** for a single-phase AC or DC array. Array controller **900** can include a peak detector **902**, a divider **904**, and an intraphase (or intra-array) balance controller **906**. Array controller **900** can receive a reference voltage waveform (Vr) and status information about each of the N modules **108** in the array (e.g., state of charge (SOCi), temperature (Ti), capacity (Qi), and voltage (Vi)) as inputs, and generate a normalized reference voltage waveform (Vrn) and modulation indexes (Mi) as outputs. Peak detector **902** detects the peak (Vpk) of Vr, which can be specific to the phase that controller **900** is operating with and/or balancing. Divider **904** generates Vrn by dividing Vr by its detected Vpk. Intraphase balance controller **906** uses Vpk along with the status information (e.g., SOCi, Ti, Qi, Vi, etc.) to generate modulation indexes Mi for each module **108** within the array **700** being controlled.

The modulation indexes and Vrn can be used to generate the switching signals for each converter **202**. The modulation index can be a number between zero and one (inclusive of zero and one). For a particular module **108**, the normalized reference Vrn can be modulated or scaled by Mi, and this modulated reference signal (Vrnm) can be used as Vref (or −Vref) according to the PWM technique described with respect to FIGS. **8**C-**8**F, or according to other techniques. In this manner, the modulation index can be used to control the PWM switching signals provided to the converter switching circuitry (e.g., S**3**-S**6** or S**1**-S**6**), and thus regulate the operation of each module **108**. For example, a module **108** being controlled to maintain normal or full operation may receive an Mi of one, while a module **108** being controlled to less than normal or full operation may receive an Mi less than one, and a module **108** controlled to cease power output may receive an Mi of zero. This operation can be performed in various ways by control system **102**, such as by MCD **112** outputting Vrn and Mi to the appropriate LCDs **114** for modulation and switch signal generation, by MCD **112** performing modulation and outputting the modulated Vrnm to the appropriate LCDs **114** for switch signal generation, or by MCD **112** performing modulation and switch signal generation and outputting the switch signals to the LCDs or the converters **202** of each module **108** directly. Vrn can be sent continually with Mi sent at regular intervals, such as once for every period of the Vrn, or one per minute, etc.

Controller **906** can generate an Mi for each module **108** using any type or combination of types of status information (e.g., SOC, temperature (T), Q, SOH, voltage, current) described herein. For example, when using SOC and T, a module **108** can have a relatively high Mi if SOC is relatively high and temperature is relatively low as compared to other modules **108** in array **700**. If either SOC is relatively low or T is relatively high, then that module **108** can have a relatively low Mi, resulting in less utilization than other modules **108** in array **700**. Controller **906** can determine Mi such that the sum of module voltages does not exceed Vpk. For example, Vpk can be the sum of the products of the voltage of each module's source **206** and Mi for that module (e.g., $Vpk=M_1V_1+M_2V_2+M_3V_3 \ldots +M_NV_N$, etc). A different combination of modulation indexes, and thus respective voltage contributions by the modules, may be used but the total generated voltage should remain the same.

Controller **900** can control operation, to the extent it does not prevent achieving the power output requirements of the system at any one time (e.g., such as during maximum acceleration of an EV), such that SOC of the energy source(s) in each module **108** remains balanced or converges to a balanced condition if they are unbalanced, and/or such that temperature of the energy source(s) or other component (e.g., energy buffer) in each module remains balanced or converges to a balanced condition if they are unbalanced. Power flow in and out of the modules can be regulated such that a capacity difference between sources does not cause an SOC deviation. Balancing of SOC and temperature can indirectly cause some balancing of SOH. Voltage and current can be directly balanced if desired, but in many embodiments the main goal of the system is to balance SOC and temperature, and balancing of SOC can lead to balance of voltage and current in a highly symmetric systems where modules are of similar capacity and impedance.

Since balancing all parameters may not be possible at the same time (e.g., balancing of one parameter may further unbalance another parameter), a combination of balancing any two or more parameters (SOC, T, Q, SOH, V, I) may be applied with priority given to either one depending on the requirements of the application. Priority in balancing can be given to SOC over other parameters (T, Q, SOH, V, I), with exceptions made if one of the other parameters (T, Q, SOH, V, I) reaches a severe unbalanced condition outside a threshold.

Balancing between arrays **700** of different phases (or arrays of the same phase, e.g., if parallel arrays are used) can be performed concurrently with intra-phase balancing. FIG. **9**B depicts an example embodiment of an Ω-phase (or Ω-array) controller **950** configured for operation in an Ω-phase system **100**, having at least Ω arrays **700**, where Ω is any integer greater than one. Controller **950** can include one interphase (or interarray) controller **910** and Ω intraphase balance controllers **906**-PA . . . **906**-PΩ for phases PA through PΩ, as well as peak detector **902** and divider **904** (FIG. **9**A) for generating normalized references VrnPA through VrnPΩ from each phase-specific reference VrPA through VrPΩ. Intraphase controllers **906** can generate Mi for each module **108** of each array **700** as described with respect to FIG. **9**A. Interphase balance controller **910** is configured or programmed to balance aspects of modules **108** across the entire multi-dimensional system, for example, between arrays of different phases. This may be achieved through injecting common mode to the phases (e.g., neutral point shifting) or through the use of interconnection modules (described herein) or through both. Common mode injection involves introducing a phase and amplitude shift to the reference signals VrPA through VrPΩ to generate normalized waveforms VrnPA through VrnPΩ to compensate for unbalance in one or more arrays, and is described further in Int'l. Publ. No. WO 2020/205574 incorporated herein.

Controllers **900** and **950** (as well as balance controllers **906** and **910**) can be implemented in hardware, software or a combination thereof within control system **102**. Controllers **900** and **950** can be implemented within MCD **112**, distributed partially or fully among LCDs **114**, or may be implemented as discrete controllers independent of MCD **112** and LCDs **114**.

Example Embodiments of Interconnection (IC) Modules

Modules **108** can be connected between the modules of different arrays **700** for the purposes of exchanging energy between the arrays, acting as a source for an auxiliary load, or both. Such modules are referred to herein as interconnection (IC) modules **108**IC. IC module **108**IC can be implemented in any of the already described module configurations (**108**A, **108**B, **108**C) and others to be described herein. IC modules **108**IC can include any number of one or more energy sources, an optional energy buffer, switch circuitry for supplying energy to one or more arrays and/or for supplying power to one or more auxiliary loads, control circuitry (e.g., a local control device), and monitor circuitry for collecting status information about the IC module itself or its various loads (e.g., SOC of an energy source, temperature of an energy source or energy buffer, capacity of an energy source, SOH of an energy source, voltage and/or current measurements pertaining to the IC module, voltage and/or current measurements pertaining to the auxiliary load(s), etc.).

FIG. **10**A is a block diagram depicting an example embodiment of a system **100** capable of producing Ω-phase power with Ω arrays **700**-PA through **700**-PΩ, where Ω can be any integer greater than one. In this and other embodiments, IC module **108**IC can be located on the rail side of arrays **700** such that the arrays **700** to which module **108**IC are connected (arrays **700**-PA through **700**-PΩ in this embodiment) are electrically connected between module **108**IC and outputs (e.g., SIO**1** and SIOΩ) to the load. Here, module **108**IC has Ω IO ports for connection to IO port **2** of each module **108**-N of arrays **700**-PA through **700**-PΩ. In the configuration depicted here, module **108**IC can perform interphase balancing by selectively connecting the one or more energy sources of module **108**IC to one or more of the arrays **700**-PA through **700**-PΩ (or to no output, or equally to all outputs, if interphase balancing is not required). System **100** can be controlled by control system **102** (not shown, see FIG. **1**A).

FIG. **10**B is a schematic diagram depicting an example embodiment of module **108**IC. In this embodiment module **108**IC includes an energy source **206** connected with energy buffer **204** that in turn is connected with switch circuitry **603**. Switch circuitry **603** can include switch circuitry units **604**-PA through **604**-PΩ for independently connecting energy source **206** to each of arrays **700**-PA through **700**-PΩ, respectively. Various switch configurations can be used for each unit **604**, which in this embodiment is configured as a half-bridge with two semiconductor switches S**7** and S**8**. Each half bridge is controlled by control lines **118-3** from LCD **114**. This configuration is similar to module **108**A described with respect to FIG. **3**A. As described with respect to converter **202**, switch circuitry **603** can be configured in any arrangement and with any switch types (e.g., MOSFET, IGBT, Silicon, GaN, etc.) suitable for the requirements of the application.

Switch circuitry units **604** are coupled between positive and negative terminals of energy source **206** and have an output that is connected to an IO port of module **108**IC. Units **604**-PA through **604**-PΩ can be controlled by control system **102** to selectively couple voltage $+V_{IC}$ or $-V_{IC}$ to the respective module I/O ports **1** through Ω. Control system **102** can control switch circuitry **603** according to any desired control technique, including the PWM and hysteresis techniques mentioned herein. Here, control circuitry **102** is implemented as LCD **114** and MCD **112** (not shown). LCD **114** can receive monitoring data or status information from monitor circuitry of module **108**IC. This monitoring data and/or other status information derived from this monitoring data can be output to MCD **112** for use in system control as described herein. LCD **114** can also receive timing information (not shown) for purposes of synchronization of modules **108** of the system **100** and one or more carrier signals (not shown), such as the sawtooth signals used in PWM (FIGS. **8**C-**8**D).

For interphase balancing, proportionally more energy from source **206** can be supplied to any one or more of arrays **700**-PA through **700**-PΩ that is relatively low on charge as compared to other arrays **700**. Supply of this supplemental energy to a particular array **700** allows the energy output of those cascaded modules **108-1** thru **108**-N in that array **700** to be reduced relative to the unsupplied phase array(s).

For example, in some example embodiments applying PWM, LCD **114** can be configured to receive the normalized voltage reference signal (Vrn) (from MCD **112**) for each of the one or more arrays **700** that module **108**IC is coupled to, e.g., VrnPA through VrnPΩ. LCD **114** can also receive modulation indexes MiPA through MiPΩ for the switch units **604**-PA through **604**-PΩ for each array **700**, respectively, from MCD **112**. LCD **114** can modulate (e.g., multiply) each respective Vrn with the modulation index for the switch section coupled directly to that array (e.g., VrnA multiplied by MiA) and then utilize a carrier signal to generate the control signal(s) for each switch unit **604**. In other embodiments, MCD **112** can perform the modulation and output modulated voltage reference waveforms for each unit **604** directly to LCD **114** of module **108**IC. In still other embodiments, all processing and modulation can occur by a single control entity that can output the control signals directly to each unit **604**.

This switching can be modulated such that power from energy source **206** is supplied to the array(s) **700** at appropriate intervals and durations. Such methodology can be implemented in various ways.

Based on the collected status information for system **100**, such as the present capacity (Q) and SOC of each energy source in each array, MCD **112** can determine an aggregate charge for each array **700** (e.g., aggregate charge for an array can be determined as the sum of capacity times SOC for each module of that array). MCD **112** can determine whether a balanced or unbalanced condition exists (e.g., through the use of relative difference thresholds and other metrics described herein) and generate modulation indexes MiPA through MiPΩ accordingly for each switch unit **604**-PA through **604**-PΩ.

During balanced operation, Mi for each switch unit **604** can be set at a value that causes the same or similar amount of net energy over time to be supplied by energy source **206** and/or energy buffer **204** to each array **700**. For example, Mi for each switch unit **604** could be the same or similar, and can be set at a level or value that causes the module **108**IC to perform a net or time average discharge of energy to the one or more arrays **700**-PA through **700**-PΩ during balanced operation, so as to drain module **108**IC at the same rate as other modules **108** in system **100**. In some embodiments, Mi for each unit **604** can be set at a level or value that does not cause a net or time average discharge of energy during balanced operation (causes a net energy discharge of zero). This can be useful if module **108**IC has a lower aggregate charge than other modules in the system.

When an unbalanced condition occurs between arrays **700**, then the modulation indexes of system **100** can be adjusted to cause convergence towards a balanced condition or to minimize further divergence. For example, control system **102** can cause module **108**IC to discharge more to the array **700** with low charge than the others, and can also cause modules **108-1** through **108**-N of that low array **700** to discharge relatively less (e.g., on a time average basis). The relative net energy contributed by module **108**IC increases as compared to the modules **108-1** through **108**-N of the array **700** being assisted, and also as compared to the amount of net energy module **108**IC contributes to the other arrays. This can be accomplished by increasing Mi for the switch unit **604** supplying that low array **700**, and by decreasing the modulation indexes of modules **108-1** through **108**-N of the low array **700** in a manner that maintains Vout for that low array at the appropriate or required levels, and maintaining the modulation indexes for other switch units **604** supplying the other higher arrays relatively unchanged (or decreasing them).

The configuration of module **108**IC in FIGS. **10**A-**10**B can be used alone to provide interphase or interarray balancing for a single system, or can be used in combination with one or more other modules **108**IC each having an energy source and one or more switch portions **604** coupled to one or more arrays. For example, a module **108**IC with Ω switch portions **604** coupled with Ω different arrays **700** can be combined with a second module **108**IC having one switch portion **604** coupled with one array **700** such that the two modules combine to service a system **100** having Ω+1 arrays **700**. Any number of modules **108**IC can be combined in this fashion, each coupled with one or more arrays **700** of system **100**.

Furthermore, IC modules can be configured to exchange energy between two or more subsystems of system **100**. FIG. **10**C is a block diagram depicting an example embodiment of system **100** with a first subsystem **1000-1** and a second subsystem **1000-2** interconnected by IC modules. Specifically, subsystem **1000-1** is configured to supply three-phase power, PA, PB, and PC, to a first load (not shown) by way of system I/O ports SIO**1**, SIO**2**, and SIO**3**, while subsystem **1000-2** is configured to supply three-phase power PD, PE, and PF to a second load (not shown) by way of system I/O ports SIO**4**, SIO**5**, and SIO**06**, respectively. For example, subsystems **1000-1** and **1000-2** can be configured as different packs supplying power for different motors of an EV or as different racks supplying power for different microgrids.

In this embodiment each module **108**IC is coupled with a first array of subsystem **1000-1** (via IO port **1**) and a first array of subsystem **1000-2** (via IO port **2**), and each module **108**IC can be electrically connected with each other module **108**IC by way of I/O ports **3** and **4**, which are coupled with the energy source **206** of each module **108**IC as described with respect to module **108**C of FIG. **3**C. This connection places sources **206** of modules **108**IC-**1**, **108**IC-**2**, and **108**IC-**3** in parallel, and thus the energy stored and supplied by modules **108**IC is pooled together by this parallel arrangement. Other arrangements such as serious connections can also be used. Modules **108**IC are housed within a common enclosure of subsystem **1000-1**, however the interconnection modules can be external to the common enclosure and physically located as independent entities between the common enclosures of both subsystems **1000**.

Each module **108**IC has a switch unit **604-1** coupled with IO port **1** and a switch unit **604-2** coupled with I/O port **2**, as described with respect to FIG. **10**B. Thus, for balancing between subsystems **1000** (e.g., interpack or inter-rack balancing), a particular module **108**IC can supply relatively more energy to either or both of the two arrays to which it is connected (e.g., module **108**IC-**1** can supply to array **700**-PA and/or array **700**-PD). The control circuitry can monitor relative parameters (e.g., SOC and temperature) of the arrays of the different subsystems and adjust the energy output of the IC modules to compensate for imbalances between arrays or phases of different subsystems in the same manner described herein as compensating for imbalances between two arrays of the same rack or pack. Because all three modules **108**IC are in parallel, energy can be efficiently exchanged between any and all arrays of system **100**. In this embodiment, each module **108**IC supplies two arrays **700**, but other configurations can be used including a single IC module for all arrays of system **100** and a configuration with one dedicated IC module for each array **700** (e.g., six IC modules for six arrays, where each IC module has one switch unit **604**). In all cases with multiple IC modules, the energy sources can be coupled together in parallel so as to share energy as described herein.

In systems with IC modules between phases, interphase balancing can also be performed by neutral point shifting (or common mode injection) as described above. Such a combination allows for more robust and flexible balancing under a wider range of operating conditions. System **100** can determine the appropriate circumstances under which to perform interphase balancing with neutral point shifting alone, interphase energy injection alone, or a combination of both simultaneously.

IC modules can also be configured to supply power to one or more auxiliary loads **301** (at the same voltage as source **206**) and/or one or more auxiliary loads **302** (at voltages stepped down from source **302**). FIG. **10**D is a block diagram depicting an example embodiment of a three-phase system **100** A with two modules **108**IC connected to perform interphase balancing and to supply auxiliary loads **301** and **302**. FIG. **10**E is a schematic diagram depicting this example embodiment of system **100** with emphasis on modules **108**IC-**1** ad **108**IC-**2**. Here, control circuitry **102** is again implemented as LCD **114** and MCD **112** (not shown). The LCDs **114** can receive monitoring data from modules **108**IC (e.g., SOC of ES**1**, temperature of ES**1**, Q of ES**1**, voltage of auxiliary loads **301** and **302**, etc.) and can output this and/or other monitoring data to MCD **112** for use in system control as described herein. Each module **108**IC can include a switch portion **602**A (or **602**B described with respect to FIG. **6**C) for each load **302** being supplied by that module, and each switch portion **602** can be controlled to maintain the requisite voltage level for load **302** by LCD **114** either independently or based on control input from MCD **112**. In this embodiment, each module **108**IC includes a switch portion **602**A connected together to supply the one load **302**, although such is not required.

FIG. **10**F is a block diagram depicting another example embodiment of a three-phase system configured to supply power to one or more auxiliary loads **301** and **302** with modules **108**IC-**1**, **108**IC-**2**, and **108**IC-**3**. In this embodiment, modules **108**IC-**1** and **108**IC-**2** are configured in the same manner as described with respect to FIGS. **10**D-**10**E. Module **108**IC-**3** is configured in a purely auxiliary role and does not actively inject voltage or current into any array **700** of system **100**. In this embodiment, module **108**IC-**3** can be configured like module **108**C of FIG. **3**B, having a converter **202**B,C (FIGS. **6**B-**6**C) with one or more auxiliary switch portions **602**A, but omitting switch portion **601**. As such, the one or more energy sources **206** of module **108**IC-**3** are interconnected in parallel with those of modules **108**IC-**1** and **108**IC-**2**, and thus this embodiment of system **100** is configured with additional energy for supplying auxiliary loads **301** and **302**, and for maintaining charge on the sources **206**A of modules **108**IC-**1** and **108**IC-**2** through the parallel connection with the source **206** of module **108**IC-**3**.

The energy source **206** of each IC module can be at the same voltage and capacity as the sources **206** of the other modules **108**-**1** through **108**-N of the system, although such is not required. For example, a relatively higher capacity can be desirable in an embodiment where one module **108**IC applies energy to multiple arrays **700** (FIG. **10**A) to allow the IC module to discharge at the same rate as the modules of the phase arrays themselves. If the module **108**IC is also supplying an auxiliary load, then an even greater capacity may be desired so as to permit the IC module to both supply the auxiliary load and discharge at relatively the same rate as the other modules.

Example Embodiments of Topologies for Applications with Intermittent Charging

Example embodiments pertaining to modular energy systems **100** used in applications with intermittently available charge sources are described with reference to FIGS. **11**A-**16**. These embodiments can be implemented with all aspects of system **100** described with respect to FIGS. **1**A-**10**F unless stated otherwise or logically implausible. As such, the many variations already described will not be repeated with respect to the following embodiments. These example embodiments are particularly suited for mobile applications, such as electric vehicles that operate on a rail (rail-based EVs) like trains, trams, trolleys, and other rolling stock, where the charge source is intermittently available. The embodiments can be used with other vehicles as well, such as cars, buses, trucks, maritime vehicles (e.g., electric ferries), planes, etc., and even in some stationary applications. Thus, for ease of description the example embodiments will be described in the context of a rail-based EV, particularly an electric tram or train, with the understanding that the embodiments have much wider applicability to other vehicles and applications.

The example embodiments can be implemented in a variety of configurations to store and deliver energy while the electric tram is moving through sections of rail where no charge source is available. FIG. **11**A is an illustration depicting a portion of an example route of an electric tram **1100** traveling on rails **1105**, where tram **1100** is traveling from a first location Stop-A to a second location Stop-B. A charge source is available within Zone-A surrounding Stop-A, and a charge source is also available within Zone-B surrounding Stop-B. The charge source can be positioned overhead, at ground-level or below ground. When within Zone-A and Zone-B, tram **1100** can extend an electrical contact device (e.g., a pantograph for a catenary) to connect to the charge source and, whether moving or stationary, can receive power for operating the loads of tram **1100** and for charging the energy sources **206** of system **100**. Zone-N demarcates the length of rails **1105** between Zone-A and Zone-B where no charge source is available. When traveling through Zone-N, the contact device can be retracted and tram **1100** uses the energy stored within its one or more systems **100** to supply power for all loads within tram **1100**.

Tram **1100** can be configured with one or more iterations of system **100**, each with its own control system **102**, and each iteration of system **100** can supply one or more loads, such as motor loads and auxiliary loads. The tram can have a single iteration of system **100** with one or more subsystems **1000** that supplies power for all loads of all cars. The one or more subsystems **1000** can share one control system **102** (e.g., a single MCD **112** for all subsystems **1000**) or can have independent control systems **102**. The cars can each have one or more subsystems **1000** of system **100** for supplying the loads within that car, or the cars can rely wholly on power supplied by a subsystem **1000** in another car. A combination of approaches can be used where a particular car has a subsystem **1000** for supplying certain loads of that particular car and that particular car can also have other loads that receive power from another subsystem **1000** in a different car.

FIG. **11**B is a block diagram depicting an example embodiment of an electric tram **1100** having two cars **1101** and **1102** with an interconnection **1103** therebetween. System **100** is located in first car **1101**, which has a retractable conductor **1104** for receiving charge from charge source **150** when conductor **1104** is in contact with source **150**. System **100** can be configured to supply high-voltage multiphase power to one or more motors within each car **1101** and **1102**. Here, system **100** has multiple arrays (not shown) for providing three-phase power (PA, PB, PC) over lines **1111** to motors **1110**-**1**A through **1110**-XA of car **1101**, where X can be any integer two or greater. Lines **1111** continue through interconnection **1103** to car **1102** where the three-phase power can be supplied to motors **1110**-**1**B through **1110**-XB of car **1102**.

System **100** can also be configured to supply multiple voltages for auxiliary loads having different power requirements, including multiphase power, single phase power, and DC power at one or more voltages each. Examples of auxiliary loads can include compressors for HVAC systems, a battery thermal management system (BTMS), onboard electrical networks for powering all automated aspects of tram **1100**, and others. Here, system **100** is configured to supply three-phase power (PD, PE, PF) to three-phase auxiliary load **1112**-**1** over lines **1113**, single phase (SP) power (line (L), neutral (N)) to single phase auxiliary load **1114**-**1** over lines **1115**, DC voltage at a first level to auxiliary load **301**-**1** over lines **1117**, and DC voltage at a second level to auxiliary load **302**-**1** over lines **1119** (see, e.g., power supply for loads **301** and **302** as described with respect to FIGS. **10**D and **10**E). Lines **1113**, **1115**, **1117**, and **1119** continue through interconnection **1103** to supply similar loads **1112**-**2**, **1114**-**2**, **301**-**2**, and **302**-**2** within car **1102**. Here, supply for the loads within car **1101** is provided in parallel fashion via the same lines for the loads within car

1102. In other embodiments, different lines can be used to supply the various loads within each car 1101 and 1102 in non-parallel fashion depending on the needs of the implementation.

One or more motors 1110 (e.g., one, two, three, four, or more) can be secured to or associated with a bogie, and the rail-based vehicle can have multiple (e.g., two or more) such bogies for every car. Placement of system 100 and its subsystems 1000 can be in close proximity to motors 1110 or elsewhere as described herein. FIG. 11C is a side view depicting an example embodiment of tram 1100 with an electrical layout of that described with respect to FIG. 11A. Here, each car includes two bogies 1120 having two motors 1110, each configured to provide motive force for driving an axle 1122. System 100 is physically located in car 1101 and can be placed in a position that would reside above the passenger's heads as shown here or below the passenger's feet or floor in an alternative embodiment. Each car includes auxiliary loads 1112, 1114, 301 and 302. All motors 1110 and auxiliary loads are supplied by system 100 via the arrows shown (individual lines 1111, 1113, 1115, 1117, and 1119 are omitted for clarity).

FIG. 11D is a block diagram depicting another example embodiment of electric tram 1100, but with multiple subsystems 1000. Each subsystem 1000 can be configured as a separate pack with a common housing. In this example, car 1101 includes a first subsystem 1000-1 for supplying power for motors 1110-1 and 1110-2 over a set of lines 1111-1 and a second subsystem 1000-2 for supplying power for motors 1110-3 and 1110-4 over a set of lines 1111-2. Car 1102 includes a third subsystem 1000-3 for supplying power for motors 1110-5 and 1110-6 over a set of lines 1111-3 and a fourth subsystem 1000-4 for supplying power for motors 1110-7 and 1110-8 over a set of lines 1111-4. Car 1102 also includes a fifth subsystem 1000-5 for supplying multiphase and/or single phase power for one or more auxiliary loads. Here, subsystem 1000-5 supplies three-phase power to auxiliary load 1112 over lines 1113 and single phase power to auxiliary load 1114 over lines 1115. Each of subsystems 1000-1 through 1000-5 can be configured to supply DC power for loads 301 and 302 by way of one or more modules 108IC or 108C (see, e.g., FIG. 3C and FIGS. 10A-10F).

Each subsystem 1000 can be connected to sets of shared lines for sharing DC power, and these lines can cross between cars 1101 and 1102 through interconnection 1103. Lines 1130 can carry high-voltage positive and negative DC signals, DC_CS+ and DC_CS−, respectively, from charge source 150, for supplying charge voltage to all of the modules 108 of each system 100 when tram 1100 is connected to a charge source 150. The shared lines can also exchange lower DC voltages for supply to auxiliary loads 301 and 302. Lines 1131 can carry positive and negative DC signals, DC1+ and DC1−, respectively, for supplying a lower DC voltage to auxiliary loads 301. For example, these lines can be similar to the lines interconnecting ports 3 and 4 of IC modules 108IC (and 108C) as described with respect to FIGS. 3C, 10D, and 10E, and can carry the voltage of the energy sources 206 of the interconnected modules 108. Lines 1132 can carry positive and negative DC signals, DC2+ and DC2−, respectively, for supplying a lower DC voltage to auxiliary loads 302. For example, these lines can be similar to the lines interconnecting ports 5 and 6 of IC modules 108IC (and 108C) as described with respect to FIGS. 3C, 10D, and 10E, and can carry a regulated stepped down voltage from sources 206.

FIG. 11E is a side view depicting another example embodiment of tram 1100 with an electrical layout of that described with respect to FIG. 11C. Here, each of subsystems 1000-1 through 1000-4 supplies power for two motors 1110 associated with axles 1122 of a bogie 1120. Subsystem 1000-5 in car 1102 supplies power for loads 1112 and 1114, which are also positioned in car 1102, but can be located in other cars as well. Each of subsystems 1000 is connected to shared lines 1130 for charging and energy exchange, as well as lines 1131 for energy exchange and supplying loads 301, and lines 1132 for supplying loads 302. As with the embodiment of FIG. 11B, each of subsystems 1000-1 through 1000-5 can be placed in a position that would reside above the passenger's heads (as shown here) or below the passenger's feet, or elsewhere.

FIG. 11F is a block diagram depicting another example embodiment of electric tram 1100 with multiple subsystems 1000, but with an auxiliary power converter 1150 instead of auxiliary subsystem 1000-5. Auxiliary converter 1150 can convert the high voltage available on DC lines 1130 into single and/or multiphase power for one or more auxiliary loads of tram 1100. In this embodiment, converter 1150 is configured to provide three phase power for three-phase load 1112 over lines 1152 and to provide single phase power for single phase load 1114 over lines 1154. When connected to charge source 150, auxiliary converter 1150 can use the DC voltage provided by source 150 over lines 1130 to power loads 1112 and 1114. As described with respect to FIG. 12B, when not connected to source 150, the other subsystems 1000-1 through 1000-4 can provide the power to auxiliary converter 1150 over lines 1130 by outputting DC voltages from ports 7 and 8 to lines 1130 using bidirectional DC-DC converters 1210. The DC output voltages from each module 108 can be summed on the DC lines 1130 to provide sufficient voltage to power auxiliary converter 1150.

The embodiments of FIGS. 11B-11F are described with respect to tram 1100 having two cars 1101 and 1102, but can be extended to rolling stock having any number of cars (one, three, four, and more), with any combination of subsystems within each car (e.g., supplying one or more motors 1110, one or more loads 1112, one or more loads 1114, one or more loads 301, and/or one or more loads 302).

The embodiments of FIGS. 11D-11F can also include one or more conventional high voltage battery packs connected between lines 1130 (DC_CS+ and DC_CS−) like subsystems 1000. The conventional battery pack can include multiple batteries (e.g., Li ion) or HED capacitors connected in series, and is not configured as a modular cascaded multi-level converter. The conventional battery pack can be used to provide supplementary power for any subsystem 1000 (through the shared DC lines 1130), for auxiliary converter 1150, directly for a motor load 1110 (if connected through an inverter), directly for DC auxiliary loads 301 and 302 (e.g., connected through a DC-DC converter), and/or directly for AC auxiliary loads 1112 and/or 1114 (if connected through a DC-AC converter). The conventional battery pack can be charged by charge source 150 through a DC-DC converter interposed in series on lines 1130 between the convention pack and charge source 150. Alternatively, the interposed DC-DC converter can be omitted and the conventional pack can be selectively disconnected from lines 1130 with switches (e.g., contactors) when charge source 150 is connected and, after disconnection of source 150, the battery pack can be reconnected to lines 1130 and charged by one or more subsystems 1000.

Modules 108A-C and 108IC described herein can be used within tram 1100. Additional example embodiments of module configurations are also described. FIG. 12A is a block diagram depicting an example embodiment of module

108D configured for use within system 100 of tram 1100. In all the embodiments described herein module 108D can include any number of energy sources 206, such as one or more batteries, one or more high energy density (HED) capacitors, and/or one or more fuel cells. If multiple batteries are included those batteries can have the same or different electrochemistries as described herein. Similarly, different types of high-energy density capacitors and fuel cells can be used. Each battery can be a single cell or multiple cells connected in series, parallel or a combination thereof to arrive at the desired voltage and current characteristics. As shown in FIG. 12A, module 108 includes a first source 206A and a second source 206B, in the sources can be batteries of different types (e.g., such as an LTO battery and an LFP battery) or one can be a battery and the other can be an HED capacitor, or any other combination as described herein.

Module 108D includes converter 202B or 202C coupled with energy sources 206A and 206B in a manner similar to that described with respect to module 108B of FIG. 3B. Energy source 206A is coupled with energy buffer 204, which in turn is coupled with a unidirectional isolated DC-DC converter 1200. Module 108D includes I/O ports 7 and 8 that connect with the charge source signals DC_CS+ and DC_CS− respectively, via lines 1130. These signals are input to DC-AC converter 1202 of converter 1200 where they are converted to high-frequency AC form and then input to transformer and rectifier section 1204.

Transformer and rectifier section 1204 can include a high-frequency transformer and one phase diode rectifier. The DC voltage on ports 7 and 8 may be a voltage that is lower than the total voltage supplied by the charge source as subsystem 1000 may include many such modules 108 receiving charge simultaneously. Transformer and rectifier section 1204 can modify the voltage of the AC signal from converter 1202, if necessary, and convert the AC signal back into DC form to charge sources 206A and 206B. Section 1204 also provides high-voltage isolation to the other components 202, 204, 206 and 114 of module 108D.

Unidirectionality is provided by virtue of the diode rectifier which permits current to be received from charge source 150 and passed to buffer 204 but does not permit outputting current in the opposite manner. For example, upon braking if the vehicle has an energy recovery system then the current from braking can be transferred back to each module 108 through power connection 110 and routed to either of sources 206A and 206B by way of converter 202B,C. Presence of unidirectional DC-DC isolated converter 1200 (diode rectifier) will prevent that recovered energy from passing through module 108D back to the charge source via lines 1130.

LCD 114 can monitor the status of converter 1200, particularly converter 1202 and section 1204, over data connections 118-5 and 118-6, respectively. As with the other components of module 108E, monitor circuitry for converter 1202 and section 1204 can be included to measure currents, voltages, temperatures, faults, and the like. These connections 118-5 and 118-6 can also supply control signals to control switching of converter 1202 and to control any active elements within section 1204. Isolation of LCD 114 can be maintained by isolation circuitry present on lines 118-5 and 118-6 (e.g., isolated gate drivers and isolated sensors).

FIG. 12B is a block diagram depicting an example embodiment of a module 108E. Module 108E is configured similarly to that of module 108D but has a bidirectional DC-DC isolated converter 1210 instead of converter 1200, and can perform bidirectional energy exchange between sources 206 (or power connection 110) and ports 7 and 8 connected to lines 1130. Bidirectional converter 1210 can route current from ports 7 and 8 to charge sources 206A and 206B (through converter 202B,C), route current from ports 7 and 8 to power the load (by output from converter 202B,C to ports 1 and 2), route current from sources 206A and/or 206B (with converter 202B,C) to ports 7 and 8 for powering one or more high voltage auxiliary loads via auxiliary converter 1150 (FIG. 11F), and route current from sources 206A and/or 206B (via converter 202B,C) to ports 7 and 8 for charging other modules 108 of system 100 by way of lines 1130.

Bidirectional converter 1210 is connected between I/O ports 7 and 8 and buffer 204 includes DC-AC converter 1202, connected to transformer 1206, which in turn is connected to AC-DC converter 1208. Converter 1202 can convert the DC voltage at ports 7 and 8 into a high-frequency AC voltage, which transformer 1206 can modify to a lower voltage if needed, and output that modified AC voltage to AC-DC converter 1208, which can convert the AC signal back into DC form for provision to sources 206A, 206B, or module ports 1 and 2. Transformer 1206 can also isolate module components 202, 204, 206, 1208, and 114 from the high voltage at ports 7 and 8. As with the other components of module 108E, monitor circuitry for converter 1202, transformer 1206, and converter 1208 can be included to measure currents, voltages, temperatures, faults, and the like. LCD 114 can monitor the status of converter 1210, particularly converter 1202, transformer 1206 (e.g., monitor circuitry or an active component associated therewith), and converter 1208, over data connections 118-5, 118-7, and 118-8, respectively. These connections 118-5 and 118-6 can also supply control signals to control switching of converter 1202 and to control any controllable elements associated with transformer 1206. Isolation of LCD 114 can be maintained by isolation circuitry present on lines 118-5 and 118-6 (e.g., isolated gate drivers and isolated sensors).

Furthermore, for electrochemical battery sources 206, the length of the charge pulses applied to sources 206 by AC-DC converter 1208 can be maintained to have a certain length, e.g., less than 5 milliseconds, to promote the occurrence of the electrochemical storage reaction in the cells without the occurrence of significant side reactions that can lead to degradation. The charge methodology can incorporate active feedback from each energy source to ensure that battery degradation, if detected, is mitigated by lowering voltage or pausing the charge routine for that module, or otherwise. Such pulses can be applied at high C rates (e.g., 5 C-15 C and greater) to enable fast charging of the sources 206. The duration and frequency of the charge pulses can be controlled by control system 102. Examples of such techniques that can be used with all embodiments described herein are described in Int'l Publ. No. WO 2020/243655, filed May 29, 2020, and titled Advanced Battery Charging on Modular Levels of Energy Storage Systems, which is incorporated by reference herein for all purposes.

FIG. 13A is a schematic diagram depicting an example embodiment of module 108D. Converter 202B is coupled with secondary source 206B, and in other embodiments can be configured like converter 202C (FIG. 6C). Buffer 204 is configured here as a capacitor. I/O ports 7 and 8 are coupled to an LC filter 1302, which is in turn coupled to bidirectional converter 1210, specifically DC-AC converter 1202, which is configured as a full bridge converter with switches S10, S11, S12, and S13. LC filter 1302 can be a distributed DC filter that can filter harmonics from and to the DC lines 1130, provide a current slowing function if desired, and/or perform other functions. The full bridge outputs from nodes N1 and N2 are connected to a primary winding of transformer **1206** within section **1204**. A secondary winding of transformer **1206** is coupled with nodes N3 and N4 of the diode rectifier of section **1204**, having diodes D1-D4. The switches of converter **1202** can be semiconductor switches configured as MOSFETs, IGBT's, GaN devices, or others as described herein. LCD **114** or another element of control system **102** can provide the switching signals for control of switches S1-S6 and S10-S13. Along with the other functions described herein, converter **202**B can be controlled to independently route current from ports **7** and **8** to source **206**B for charging, or to I/O ports **1** and **2** for powering the motor loads **1110**.

FIG. **13**B is a schematic diagram depicting an example embodiment of module **108**E. Converter **202**B is coupled with secondary source **206**B, and in other embodiments can be configured like converter **202**C (FIG. **6**C). Buffer **204** is configured as a capacitor. I/O ports **7** and **8** are coupled to an LC filter **1302**, which is in turn coupled to bidirectional converter **1210**, specifically DC-AC converter **1202**, which is configured as a full bridge converter with switches S**10**, S**11**, S**12**, and S**13**. The full bridge outputs from nodes N**1** and N**2** are connected to a primary winding of transformer **1206**. A secondary winding of transformer **1206** is coupled with nodes N**3** and N**4** of a second full bridge circuit configured as AC-DC converter **1208**, having switches S**14**, S**15**, S**16**, and S**17**. The switches of converter **1208** can be semiconductor switches configured as MOSFETs, IGBT's, GaN devices, or others as described herein. LCD **114** or another element of control system **102** can provide the switching signals for control of switches S**1**-S**6** and S**10**-S**17**. Along with the other functions described herein, converter **202**B can be controlled to independently route current from ports **7** and **8** to source **206**B for charging, or to I/O ports **1** and **2** for powering the motor loads.

FIG. **13**C is a schematic diagram depicting another example embodiment of module **108**E, where AC-DC converter **1208** is configured as a push-pull converter with a first terminal of source **206** connected to one side of dual secondary windings of transformer **1206** through an inductor L**2**, and switches S**18** and S**19** connected between the opposite side of dual secondary windings and a common node (e.g., node **4**) coupled with the opposite terminal of source **206**. The push-pull configuration only requires two switches and thus is more cost-effective than a full bridge converter, although the switches have larger voltages applied across them.

FIG. **14**A is a block diagram depicting an example embodiment of subsystem **1000** configured to supply three-phase power for two motors **1110-1** and **1110-2** in parallel. This embodiment includes three serial arrays **700**-PA, **700**-PB, and **700**-PC with modules **108** arranged in cascaded fashion with ports **1** and **2** daisy-chained between modules as described elsewhere herein. Subsystem **1000** has three arrays **700**-PA, **700**-PB, and **700**-PC for supplying three-phase power to one or more loads **1112** by way of system ports SIO**1**, SIO**2**, and SIO**3**. In this embodiment and that of FIG. **14**B, each of modules **108** can be configured as module **108**D (FIG. **12**A) or module **108**E (FIGS. **12**B, **13**A, **13**B). A neutral signal is available at SIO**6**(N) if desired. The DC voltage signals DC_CS+ and DC_CS− supplied from lines **1130** are supplied to subsystem **1000** by system I/O ports SIO**4** and SIO**5**, respectively. Ports **7** and **8** of each of modules **108** are daisy-chained such that the applied charge source voltage is divided across modules **108-1** through **108**-N of each array **700**. As with other embodiments, subsystem **1000** can be configured with N modules **108** in each array **700**, where N can be any integer two or greater.

FIG. **14**B is a block diagram depicting another example embodiment of subsystem **1000** configured to supply three-phase power for motors **1110-1** and **1110-2**, and also having modules **108**IC-**1**, **108**IC-**2**, and **108**IC-**3**. Modules **108**IC can have interconnected energy sources **206** and can be configured for interphase balancing between arrays **700** as described elsewhere herein. Modules **108**IC can also be configured to supply DC voltages to lines **1131** and **1132** for one or more auxiliary loads **301** and/or one or more auxiliary loads **302**. The example embodiments of FIGS. **14**A and **14**B can be used as any of the subsystems **1000-1** through **1000-4** as described with respect to FIGS. **11**D and **11**E, depending on whether each subsystem **1000** is configured to supply power for auxiliary loads and is configured with interphase balancing capability through interconnected modules **108**IC.

FIGS. **14**C and **14**D are schematic diagrams depicting example embodiments of module **108**IC configured for use with the embodiment of FIG. **14**B. In this embodiment module **108**IC is configured with a single switch portion **604** configured to connect IO port **1** to either positive DC voltage of source **206** (port **3**) or negative DC voltage of source **206** (port **4**). A switch portion **602**A regulates and steps down the voltage of source **206** for provision as the auxiliary load voltage for lines **1132**. A filter capacitor C**3** can be placed across ports **5** and **6**. Module **108**IC includes bidirectional converter **1210** configured with two full bridge converters similar to that of FIG. **13**A. FIG. **14**D depicts another embodiment where AC-DC converter **1208** is configured as a push-pull converter similar to the embodiment of FIG. **13**B.

FIG. **15** is a block diagram depicting an example embodiment of subsystem **1000-5** configured to supply multiphase, single phase, and DC power for auxiliary loads of tram **1100**. Subsystem **1000-5** has three arrays **700**-PD, **700**-PE, and **700**-PF for supplying three-phase power to one or more loads **1112** by way of system ports SIO**1**, SIO**2**, and SIO**3**. Subsystem **1000-5** has a fourth array **700**-PG for supplying single phase power to one or more loads **1114** by way of system outputs SIO**6** (SP(L)) and SIO**7** (SP(N)). Subsystem **1000-5** can be configured to supply power of as many different phases as necessary through the addition of further arrays **700**. A number of modules **108** within each array can be varied depending on the voltage requirements of the load. For example, although all arrays **700** are shown here as having N modules **108**, the value of N can differ between arrays. Each of the N modules **108** of each array **700** can be configured like module **108**D (FIG. **13**A) or module **108**E (FIG. **13**B).

Each array **700** can also include a module **108**IC having interconnected sources **206** for energy sharing and interphase balancing. Modules **108**IC-**1** through **108**IC-**3** can be configured like the embodiments described with respect to FIGS. **14**A and **14**B. FIG. **16** is a block diagram depicting an example embodiment of module **108**IC-**4** for use in single phase array **700**-PD. This embodiment is similar to that of FIG. **14**A, except module **108**IC-**4** includes two switch portions **604-1** and **604-2**. Portions **604-1** and **604-2** are configured to independently connect IO ports **1** and **2**, respectively, to either VDCL+ (port **3**) or VDCL− (port **4**). I/O port **1** can be connected to port **2** of module **108**-N of array **700**-PD as shown in FIG. **15**. I/O port **2** can serve as a neutral for the power provided by array **700**-PD. An LC circuit **1600** can be connected between ports **1** and **2** as shown to provide filtering of harmonics.

In some embodiments, a separate subsystem **1000** may not be needed to generate the requisite three-phase and single phase voltages for auxiliary loads. In such embodiments, subsystem **1000-5** can be omitted and an auxiliary power converter can be used to instead generate the three-phase in single phase auxiliary load voltages. This auxiliary converter can be connected to DC charge source lines **1130** and can receive power either from charge source **150** or the other subsystems **1000** when charge source **150** is not connected.

The use of bidirectional converters **1210** in the modules of subsystems **1000-1** through **1000-5** allows those subsystems to supply relatively higher DC voltages across lines **1130**, for example in a configuration where a large auxiliary load, such as a battery thermal management system (BTMS), is powered directly from lines **1130**. In such an instance the auxiliary load connected across lines **1130** can be powered directly by the charge source when connected to tram **1100** and then can be powered by one or more subsystems **1000** outputting power from sources **206** through bidirectional converters **1210** of each module **108**.

The embodiments disclosed herein are not limited to operation with any particular voltage, current, or power. By way of example and for purposes of context, in one sample implementation charge source **150** may provide a voltage of 600-1000V on lines **1130**. Each of subsystems **1000-1** through **1000-4** may provide multiphase voltages that are regulated and stabilized by voltage and frequency if required, in those voltages may be 300-1000V depending on the needs of the motors. An example three-phase auxiliary voltage for load **1112** can be 300-500V, regulated and stabilized as needed. An example single phase auxiliary voltage for load **1114** can be 120-240V, regulated and stabilized as needed. Example auxiliary voltages for load **301** can be 48-60V and example auxiliary voltages for load **302** can be 24-30V. Again these are examples only for purposes of context and the voltages that system **100** can provide will vary depending on the needs of the application.

To maintain a balanced overall system, the energy of sources **206** of auxiliary subsystem **1000-5** can be transferred to any of the (non-auxiliary) subsystems **1000-1** through **1000-4** by way of lines **1131** and the shared interconnection module connections, and this energy can be used either for charging those subsystems **1000-1** through **1000-4** or supply to the motors. Thus energy from auxiliary subsystem **1000-5** can be used to power one or more motors even though not directly connected to those motors, but rather indirectly connected to those motors by way of one or more other subsystems **1000-1** through **1000-4**. Similarly, energy recovered through braking can be shared between subsystems **1000-1** through **1000-5** by way of lines **1131** and the shared interconnection module connections.

Various aspects of the present subject matter are set forth below, in review of, and/or in supplementation to, the embodiments described thus far, with the emphasis here being on the interrelation and interchangeability of the following embodiments. In other words, an emphasis is on the fact that each feature of the embodiments can be combined with each and every other feature unless stated otherwise.

In many embodiments, a modular energy system controllable to supply power to a load is provided, the system including: a plurality of modules connected together to output an AC voltage signal including a superposition of first output voltages from each module, where each module includes: an energy source; a first converter connected to the energy source and configured to generate the first output voltage at a first port of the module; and a second converter connected between a second port of the module and the energy source, where the second converter is configured to receive a charge signal at the second port and convert the charge signal into a second output voltage to charge the energy source.

In some embodiments, the first converter includes a plurality of switches. The system where the plurality of switches can be configured as a full bridge converter.

In some embodiments, the second converter is a DC-DC converter including a transformer configured to isolate the energy source and the first converter from the second port. The system where the second converter can include a DC-AC converter connected between the second port and the transformer. The system where the second converter can include a diode rectifier connected between the transformer and the energy source. The system where the second converter can include an AC-DC converter connected between the transformer and the energy source. The system where the AC-DC converter can be configured as a full bridge converter or a push-pull converter. The system where the second converter can be a unidirectional converter that conducts electricity from the second port to the energy source. The system where the second converter can be a bidirectional converter that conducts electricity between the second port and the energy source.

In some embodiments, the plurality of modules are serially connected as an array and are connected to receive a total charge source voltage such that a voltage of the charge signal applied to the second port of each module is divided down from the total charge source voltage. The system where the energy source can be a first energy source, and where each module can include a second energy source. The system where the second energy source can be connected to the first converter by an inductor. The system where the first energy source can be a lithium ion battery of a first type and the second energy source can be a lithium ion battery of a second type, where the first and second types can be different. The system where the first energy source can be a battery and the second energy source can be a high energy density (HED) capacitor.

In some embodiments, each module can further include an energy buffer connected in parallel with the energy source. The system where the energy buffer can be a capacitor.

In some embodiments, the system can further include a control system configured to control switching of the first and second converters. The system where the control system can include a plurality of local control devices associated with the plurality of modules, and a master control device communicatively coupled with the plurality of local control devices. The system where the control system can be configured to control switching of the second converter of each module to exchange energy between energy sources of the modules.

In many embodiments, a modular energy system controllable to supply power to a load is provided, the system including: a first array including a first plurality of modules connected together to output a first AC voltage signal including a superposition of output voltages from the first plurality of modules; and a second array including a second plurality of modules connected together to output a second AC voltage signal including a superposition of output voltages from the second plurality of modules, where each module of the first plurality and second plurality of modules includes: an energy source; a first converter connected to the energy source and configured to generate the output voltage at a first port of the module; and a second converter connected to a second port of the module and the energy source, where the second converter is configured to receive a charge signal at the second port and convert the charge signal into a charge voltage to charge the energy source.

In some embodiments, the system can further include a first interconnection module coupled with the first array and a second interconnection module coupled with the second array, where the first and second interconnection modules each include: a first port and a second port; an energy source; a first converter connected to the energy source and configured to generate an output voltage at the first port; and a second converter connected to the second port and the energy source, where the second converter is configured to receive a charge signal at the second port and convert the charge signal into a charge voltage to charge the energy source. The system where the energy sources of the first and second interconnection modules can be connected in parallel. The system where the first interconnection module can be configured to supply power for an auxiliary load. The system where the first interconnection module can include a third port configured to connect the energy source of the first interconnection module to an auxiliary load. The system where the first interconnection module can include a third port configured to connect the energy source of the first interconnection module through switch circuitry and an inductor of the first interconnection module to an auxiliary load external to the first interconnection module. The system can further include a control system configured to control the first converter of each of the first and second interconnection modules to balance energy between the first and second arrays. The system cam further include a control system configured to control the first converter of each of the first and second interconnection modules to balance energy between the first and second arrays.

In some embodiments, the first converter can include a plurality of switches. The system where the plurality of switches can be configured as a full bridge converter.

In some embodiments, the system where the second converter can be a DC-DC converter including a transformer configured to isolate the energy source and the first converter from the second port. The system where the second converter can include a DC-AC converter connected between the second port and the transformer. The system where the second converter can include a diode rectifier connected between the transformer and the energy source. The system where the second converter can include an AC-DC converter connected between the transformer and the energy source. The system where the AC-DC converter can be configured as a full bridge converter or a push-pull converter. The system where the second converter can be a unidirectional converter that conducts electricity from the second port to the energy source. The system where the second converter can be a bidirectional converter that conducts electricity between the second port and the energy source.

In some embodiments, the first plurality of modules are serially connected in the first array and are connected to receive a total charge source voltage such that a voltage of the charge signal applied to the second port of each module of the first array is divided down from the total charge source voltage.

In some embodiments, the energy source is a first energy source, and where each module can include a second energy source. The system where the second energy source can be connected to the first converter by an inductor. The system where the first energy source can be a lithium ion battery of a first type and the second energy source can be a lithium ion battery of a second type, where the first and second types can be different. The system where the first energy source can be a battery and the second energy source can be a high energy density (HED) capacitor.

In some embodiments, each module of the first plurality of modules, each module of the second plurality of modules, the first interconnection module, and the second interconnection module further including an energy buffer connected in parallel with the energy source. The system where the energy buffer can be a capacitor.

In some embodiments, the system further including a control system configured to control switching of the first and second converters. The system where the control system can include a plurality of local control devices associated with the plurality of modules, and a master control device communicatively coupled with the plurality of local control devices. The system where the control system can be configured to control switching of the second converter of each module to exchange energy between energy sources of the modules.

In many embodiments, a modular energy system controllable to supply power to loads of an electric vehicle in provided, the system including: a first plurality of modules connected together in first, second, and third arrays, each array configured to output an AC voltage signal including a superposition of output voltages from the modules of that array; and a second plurality of modules connected together in a fourth array configured to output an AC voltage signal including a superposition of output voltages from the second plurality of modules, where the first plurality of modules are configured to provide three-phase power to a first auxiliary load of the electric vehicle, and where the second plurality of modules are configured to provide single phase power to a second auxiliary load of the electric vehicle.

In some embodiments, the system further including a plurality of interconnection modules connected to the first, second, third, and fourth arrays. The system where a first interconnection module of the plurality of interconnection modules can be configured to provide DC power to a third auxiliary load of the electric vehicle. The system where the first interconnection module can include an energy source and can be configured to connect the energy source to the third auxiliary load. The system where the first interconnection module can include an energy source and can be configured to connect the energy source through switch circuitry and an inductor of the first interconnection module to the third auxiliary load.

In some embodiments, all of the modules individually include: an energy source; a first converter connected to the energy source and configured to generate the output voltage at a first port of the module; and a second converter connected to a second port of the module and the energy source, where the second converter is configured to receive a charge signal at the second port and convert the charge signal into a charge voltage to charge the energy source. The system can further include a control system configured to control the first converter of each of the plurality of interconnection modules to balance energy between the first, second, third, and fourth arrays. The system where modules of the first array can be serially connected to receive a total charge source voltage such that a voltage of the charge signal applied to the second port of each module of the first array is divided down from the total charge source voltage. The system where the first array, second array, and third array can be connected in parallel to receive a total charge source voltage such that a voltage of the charge signal applied to the second port of each module of each array is divided down from the total charge source voltage.

In some embodiments, every module further includes an energy buffer. The system where the energy buffer is a capacitor.

In some embodiments, the system further including a control system configured to control each of the modules.

In many embodiments, a modular energy system controllable to supply power to a load is provided, the system including: a plurality of modules connected together to output an AC voltage signal including a superposition of first output voltages from each module, where each module includes an energy source, a first converter connected to the energy source and configured to generate the first output voltage at a first port of the module, and a second converter connected between a second port of the module and the energy source; and a control system configured to control the first converter and the second converter of each module.

In some embodiments, the control system is configured to control the first converter of each module to output the first output voltage according to a pulse width modulation technique. The system where the control system can be configured to control the second converter of each module to charge the energy source of the module.

In some embodiments, the control system is configured to control the second converter of each module to charge the energy source of the module and concurrently control the first converter of each module to output the first output voltage. The system where at least a subset of modules of the plurality of modules can be connected together in cascaded fashion such that the first port of each module in the subset is coupled to a first port of another module in the subset and the second port of each module in the subset is coupled to a second port of another module in the subset. The system where the control system can be configured to control the second converter of a first module in the plurality of modules and the second converter of a second module in the plurality of modules to exchange energy between the energy source of the first module and the energy source of the second module.

In some embodiments, the second converter of each module of the plurality of modules is a DC-DC converter including a transformer configured to isolate the energy source and the first converter from the second port. The system where the second converter of each module of the plurality of modules can include a DC-AC converter connected between the second port and the transformer. The system where the second converter of each module of the plurality of modules can include a diode rectifier connected between the transformer and the energy source. The system where the second converter of each module of the plurality of modules can include an AC-DC converter connected between the transformer and the energy source. The system where the AC-DC converter can be configured as a full bridge converter or a push-pull converter.

In some embodiments, the energy source is a first energy source, and where each module of the plurality of modules includes a second energy source coupled with the first converter by way of an inductor.

In some embodiments, the control system includes a plurality of local control devices associated with the plurality of modules, and a master control device communicatively coupled with the plurality of local control devices.

In some embodiments, the first plurality of modules are connected together in first, second, and third arrays, each configured to output an AC voltage signal including a superposition of output voltages from the modules of that array. The system can further include a second plurality of modules connected together in fourth, fifth, and sixth arrays, each configured to output an AC voltage signal including a superposition of output voltages from the modules of that array. The system can further include a third plurality of modules connected together in a seventh array configured to output an AC voltage signal including a superposition of output voltages from the third plurality of modules. The system where the first plurality of modules can be configured to provide three-phase power to a motor of the electric vehicle, the second plurality of modules can be configured to provide three-phase power to a first auxiliary load of the electric vehicle, and the third plurality of modules can be configured to provide single phase power to a second auxiliary load of the electric vehicle. The system where the control system can be configured to control a first converter and a second converter of each module of the second and third pluralities of modules.

In some embodiments, the system further includes an auxiliary converter coupled to DC lines of the system, the auxiliary converter configured to convert DC power from the DC lines to AC power for an auxiliary load. The control system can be configured to control the second converter of each module to output a DC voltage from the second port of each module such that the output DC voltages are applied to the DC lines to power the auxiliary converter.

In many embodiments, a method of operating a rail-based electric vehicle including a modular energy storage system is provided, the method including: outputting an AC power signal, including a plurality of first output voltages from a plurality of modules, to an electric motor of the rail-based electric vehicle, where the plurality of modules each include an energy source, a first converter coupled with the energy source and configured to output the first output voltage from a first port of the module, and a second converter coupled between the energy source and a second port of the module; applying a charge signal to electric vehicle, where voltage from the charge signal is applied to the second port of each of the plurality of modules; and controlling the second converter of each of the plurality of modules to charge the energy source of each module. The method where the electric vehicle can be moving while the charge signal is applied.

The term "module" as used herein refers to one of two or more devices or subsystems within a larger system. The module can be configured to work in conjunction with other modules of similar size, function, and physical arrangement (e.g., location of electrical terminals, connectors, etc.). Modules having the same function and energy source(s) can be configured identical (e.g., size and physical arrangement) to all other modules within the same system (e.g., rack or pack), while modules having different functions or energy source(s) may vary in size and physical arrangement. While each module may be physically removable and replaceable with respect to the other modules of the system (e.g., like wheels on a car, or blades in an information technology (IT) blade server), such is not required. For example, a system may be packaged in a common housing that does not permit removal and replacement any one module, without disassembly of the system as a whole. However, any and all embodiments herein can be configured such that each module is removable and replaceable with respect to the other modules in a convenient fashion, such as without disassembly of the system.

The term "master control device" is used herein in a broad sense and does not require implementation of any specific protocol such as a master and slave relationship with any other device, such as the local control device.

The term "output" is used herein in a broad sense, and does not preclude functioning in a bidirectional manner as both an output and an input. Similarly, the term "input" is used herein in a broad sense, and does not preclude functioning in a bidirectional manner as both an input and an output.

The terms "terminal" and "port" are used herein in a broad sense, can be either unidirectional or bidirectional, can be an input or an output, and do not require a specific physical or mechanical structure, such as a female or male configuration.

Different reference number notations are used herein. These notations are used to facilitate the description of the present subject matter and do not limit the scope of that subject matter. Some figures show multiple instances of the same or similar elements. Those elements may be appended with a number or a letter in a "-X" format, e.g., 123-1, 123-2, or 123-PA. This -X format does not imply that the elements must be configured identically in each instance, but is rather used to facilitate differentiation when referencing the elements in the figures. Reference to a genus number without the -X appendix (e.g., 123) broadly refers to all instances of the element within the genus.

Various aspects of the present subject matter are set forth below, in review of, and/or in supplementation to, the embodiments described thus far, with the emphasis here being on the interrelation and interchangeability of the following embodiments. In other words, an emphasis is on the fact that each feature of the embodiments can be combined with each and every other feature unless explicitly stated otherwise or logically implausible.

Processing circuitry can include one or more processors, microprocessors, controllers, and/or microcontrollers, each of which can be a discrete or stand-alone chip or distributed amongst (and a portion of) a number of different chips. Any type of processing circuitry can be implemented, such as, but not limited to, personal computing architectures (e.g., such as used in desktop PC's, laptops, tablets, etc.), programmable gate array architectures, proprietary architectures, custom architectures, and others. Processing circuitry can include a digital signal processor, which can be implemented in hardware and/or software. Processing circuitry can execute software instructions stored on memory that cause processing circuitry to take a host of different actions and control other components.

Processing circuitry can also perform other software and/or hardware routines. For example, processing circuitry can interface with communication circuitry and perform analog-to-digital conversions, encoding and decoding, other digital signal processing, multimedia functions, conversion of data into a format (e.g., in-phase and quadrature) suitable for provision to communication circuitry, and/or can cause communication circuitry to transmit the data (wired or wirelessly).

Any and all communication signals described herein can be communicated wirelessly except where noted or logically implausible. Communication circuitry can be included for wireless communication. The communication circuitry can be implemented as one or more chips and/or components (e.g., transmitter, receiver, transceiver, and/or other communication circuitry) that perform wireless communications over links under the appropriate protocol (e.g., Wi-Fi, Bluetooth, Bluetooth Low Energy, Near Field Communication (NFC), Radio Frequency Identification (RFID), proprietary protocols, and others). One or more other antennas can be included with communication circuitry as needed to operate with the various protocols and circuits. In some embodiments, communication circuitry can share antenna for transmission over links. RF communication circuitry can include a transmitter and a receiver (e.g., integrated as a transceiver) and associated encoder logic.

Processing circuitry can also be adapted to execute the operating system and any software applications, and perform those other functions not related to the processing of communications transmitted and received.

Computer program instructions for carrying out operations in accordance with the described subject matter may be written in any combination of one or more programming languages, including an object oriented programming language such as Java, JavaScript, Smalltalk, C++, C#, Transact-SQL, XML, PHP or the like and conventional procedural programming languages, such as the "C" programming language or similar programming languages.

Memory, storage, and/or computer readable media can be shared by one or more of the various functional units present, or can be distributed amongst two or more of them (e.g., as separate memories present within different chips). Memory can also reside in a separate chip of its own.

To the extent the embodiments disclosed herein include or operate in association with memory, storage, and/or computer readable media, then that memory, storage, and/or computer readable media are non-transitory. Accordingly, to the extent that memory, storage, and/or computer readable media are covered by one or more claims, then that memory, storage, and/or computer readable media is only non-transitory. The terms "non-transitory" and "tangible" as used herein, are intended to describe memory, storage, and/or computer readable media excluding propagating electromagnetic signals, but are not intended to limit the type of memory, storage, and/or computer readable media in terms of the persistency of storage or otherwise. For example, "non-transitory" and/or "tangible" memory, storage, and/or computer readable media encompasses volatile and non-volatile media such as random access media (e.g., RAM, SRAM, DRAM, FRAM, etc.), read-only media (e.g., ROM, PROM, EPROM, EEPROM, flash, etc.) and combinations thereof (e.g., hybrid RAM and ROM, NVRAM, etc.) and variants thereof.

It should be noted that all features, elements, components, functions, and steps described with respect to any embodiment provided herein are intended to be freely combinable and substitutable with those from any other embodiment. If a certain feature, element, component, function, or step is described with respect to only one embodiment, then it should be understood that that feature, element, component, function, or step can be used with every other embodiment described herein unless explicitly stated otherwise. This paragraph therefore serves as antecedent basis and written support for the introduction of claims, at any time, that combine features, elements, components, functions, and steps from different embodiments, or that substitute features, elements, components, functions, and steps from one embodiment with those of another, even if the following description does not explicitly state, in a particular instance, that such combinations or substitutions are possible. It is explicitly acknowledged that express recitation of every possible combination and substitution is overly burdensome, especially given that the permissibility of each and every such combination and substitution will be readily recognized by those of ordinary skill in the art.

As used herein and in the appended claims, the singular forms "a," "an," and "the" include plural referents unless the context clearly dictates otherwise.

While the embodiments are susceptible to various modifications and alternative forms, specific examples thereof have been shown in the drawings and are herein described in detail. It should be understood, however, that these embodiments are not to be limited to the particular form disclosed, but to the contrary, these embodiments are to cover all modifications, equivalents, and alternatives falling within the spirit of the disclosure. Furthermore, any features, functions, steps, or elements of the embodiments may be recited in or added to the claims, as well as negative limitations that define the inventive scope of the claims by features, functions, steps, or elements that are not within that scope.

The invention claimed is:

1. A modular energy system controllable to supply power to a load, comprising:

a plurality of modules connected together to output an AC voltage signal comprising a superposition of first output voltages from each module,

wherein each module comprises:

an energy source;

a first converter connected to the energy source and configured to generate the first output voltage at a first port of the module, wherein the first converter is a DC-AC converter; and

a second converter connected between a second port of the module and the energy source, wherein the second converter is a DC-DC converter configured to receive an input signal and convert the input signal into a second output voltage.

2. The system of claim **1**, wherein the first converter comprises a plurality of switches.

3. The system of claim **2**, wherein the plurality of switches are configured as a full bridge converter.

4. The system of claim **1**, wherein the second converter comprises a transformer configured to isolate the energy source and the first converter from the second port.

5. The system of claim **4**, wherein the second converter comprises a DC-AC converter connected between the second port and the transformer.

6. The system of claim **5**, wherein the second converter comprises a diode rectifier connected between the transformer and the energy source.

7. The system of claim **4**, wherein the second converter comprises an AC-DC converter connected between the transformer and the energy source.

8. The system of claim **7**, wherein the AC-DC converter is configured as a full bridge converter or a push-pull converter.

9. The system of claim **4**, wherein the second converter is a unidirectional converter that conducts electricity from the second port to the energy source.

10. The system of claim **4**, wherein the second converter is a bidirectional converter that conducts electricity between the second port and the energy source.

11. The system of claim **1**, wherein the plurality of modules are serially connected as an array and are connected to receive a total charge source voltage such that a voltage of the input signal applied to the second port of each module is divided down from the total charge source voltage.

12. The system of claim **1**, wherein the energy source is a first energy source, and wherein each module comprises a second energy source.

13. The system of claim **12**, wherein the second energy source is connected to the first converter by an inductor.

14. The system of claim **12**, wherein the first energy source is a lithium ion battery of a first type and the second energy source is a lithium ion battery of a second type, wherein the first and second types are different.

15. The system of claim **12**, wherein the first energy source is a battery and the second energy source is a high energy density (HED) capacitor.

16. The system of claim **1**, wherein each module further comprises an energy buffer connected in parallel with the energy source.

17. The system of claim **16**, wherein the energy buffer is a capacitor.

18. The system of claim **1**, further comprising a control system configured to control switching of the first and second converters.

19. The system of claim **18**, wherein the control system comprises a plurality of local control devices associated with the plurality of modules, and a master control device communicatively coupled with the plurality of local control devices.

20. The system of claim **18**, wherein the control system is configured to control switching of the second converter of each module to exchange energy between energy sources of the modules.

21. The system of claim **1**, wherein the input signal is a charge signal and the second converter is configured to receive the charge signal at the second port and convert the charge signal into the second output voltage to charge the energy source.

22. The system of claim **1**, wherein the input signal is an output voltage of the energy source and the second converter is configured to convert the output voltage of the energy source to a supply voltage for an auxiliary converter.

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